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EXHAUST EMISSIONS FROM UNCONTROLLED VEHICLES AND RELATED EQUIPMENT USING INTERNAL COMBUSTION ENGINES. PART 2: OUTBOARD MOTORS

Charles T. Hare, et al

Southwest Research Institute

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EXHAUST EMISSIONS FROM UNCONTROLLED VEHICLES AND RELATED EQUIPMENT USING INTERNAL COMBUSTION ENGINES

by

Charles T. Hare

Karl J. Springer

FINAL REPORT

PART 2

OUTBOARD MOTORS

Contract No. EHS 70-108

Prepared for

Characterization and Control Development Branch

Mobile Source Pollution Control Program

and

National Air Data Branch

Office of Air Quality Planning and Standards

Office of Air and Water Programs

Environmental Protection Agency

January 1973

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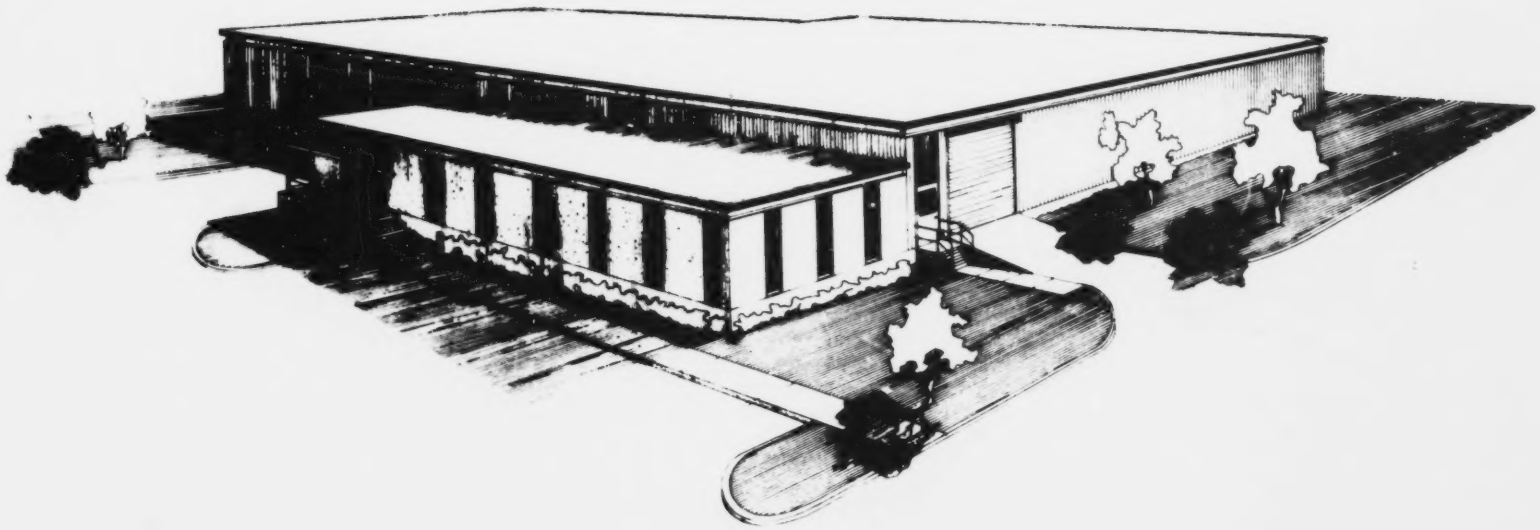

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Environmental Protection Agency

January 1973

Approved:

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Department of Automotive Research

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ABSTRACT

This report is Part 2 of the Final Report on Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines, Contract EHS 70-108. Exhaust emissions from four 2-stroke outboard motors were measured before and after being bubbled through water, and the constituents measured were: total hydrocarbons by FIA; CO, CO_2, NO, and hydrocarbons by NDIR; NO and NO_x by chemiluminescence; O_2 by electrochemical analysis; light hydrocarbons by gas chromatograph; and total aliphatic aldehydes and formaldehyde by the MBTH and chromotropic acid methods, respectively.

The engines tested were a Chrysler 35 hp twin, a Mercury 65 hp in-line four, and OMC twins of 4 hp and 9.5 hp. The engines were operated on stationary test stands with power absorption by electric (eddy current) dynamometers driven from the propeller shafts. Pertinent operating data were recorded along with emissions, and mass emissions computed from data gathered during this project are used in conjunction with available sales and usage data to estimate national emissions impact.

FOREWORD

The project for which this report constitutes part of the end product was initiated jointly on June 29, 1970 by the Division of Motor Vehicle Research and Development and the Division of Air Quality and Emission Data, both divisions of the agency known as NAPCA. Currently, these offices are the Characterization and Control Development Branch of MSPCP and the Air Quality Management Branch of SSPCP, respectively, Office of Air Programs, Environmental Protection Agency. The contract number is EHS 70-108, and the project is identified within Southwest Research Institute as 11-2869-01.

This report (Part 2) covers the outboard motor portion of the characterization work only, and the other items in the characterization work have been or will be covered by six other parts of the final report. In the order in which the final reports have been or will be submitted, the seven parts of the characterization work include; Locomotives and Marine Counterparts; Outboard Motors; Motorcycles; Small Utility Engines; Farm, Construction, and Industrial Engines; Snowmobiles; and Gas Turbine "Peaking" Powerplants. Other efforts which have been conducted as separate phases of Contract EHS 70-108, including: measurment of gaseous emissions from a number of aircraft turbine engines; measurement of crankcase drainage from a number of outboard motors; and investigation of emissions control technology for locomotive diesel engines; either have been or will be reported separately.

Cognizant technical personnel for the Environmental Protection Agency are currently Messrs. William Rogers Oliver and David S. Kircher, and past Project Officers include Messrs. J. L. Raney, A. J. Hoffman, B. D. McNutt, and G. J. Kennedy. Project Manager for Southwest Research Institute has been Mr. Karl J. Springer, and Mr. Charles T. Hare has carried the technical responsibility.

The offices of the Environmental Protection Agency which have sponsored this project are located at 2565 Plymouth Road, Ann Arbor, Michigan 49105 (MSPCP), and Research Triangle Park, North Carolina 27711 (SSPCP). The contractor (SwRI) is located at 8500 Culebra Road, San Antonio, Texas 78284.

The successful conduct of the outboard motor portion of the project owes a great deal to assistance rendered by the Boating Industry Association, Outboard Marine Corporation, Chrysler Outboard Corporation, and Mercury Marine. The advice and cooperation of Mike Boerma of OMC, Jerry Pok of Chrysler, Ted Morgan and Joe Swift of Mercury, and Don Reed of BIA have been especially valued and appreciated. David Cole of the University of Michigan also provided some initial testing guidelines.

The personnel involved in preparation for and conduct of the outboard tests included Russel T. Mack, lead technician, and Jimmie Chessher, Gene Hoyt, Ernest Krueger, Joyce McBryde, Nathan Reeh, and Joyce Winfield. All these people made valuable contributions, especially Rusty Mack, whose ingenuity and familiarity with the equipment helped make a really complicated sampling system workable.

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I. INTRODUCTION

The program of research on which this report is based was initiated by the Environmental Protection Agency to (1) characterize emissions from a broad range of internal combustion engines in order to accurately set priorities for future control, as required, and (2) assist in developing more inclusive national and regional pollution inventories. This document, which is Part 2 of a planned seven-part final report, concerns emissions from outboard motors and the national impact of these emissions.

Prior to the subject program, very little quantitative research on outboard motor emissions had been performed, and the results of the small amount of previous work were not available. The experience of several manufacturers in performance testing, however, was made available and proved to be very valuable. At the time of the tests, only little consideration had been given to standardized emissions test procedures for outboards by professional groups, so no well thought-out procedures had been written. As a consequence of the general lack of knowledge on the subject, procedures were developed which would fulfill project requirements as well as possible, but little consideration has been given to their potential usefulness for anything except research purposes.

All the outboard motor exhaust emissions testing was performed in the Emissions Research Laboratory between January 1 and August 10, 1972, although not continuously. As an additional task (Task VII) under the same contract, however, a separate research program is being performed to evaluate crankcase drainage emissions from in-service outboard motors. This latter task will be considered in this report only insofar as it affects exhaust emissions, and the impact of the drainage itself will be treated in a separate Final Report on Task VII.

II. OBJECTIVES

The primary objectives of the outboard motor portion of this project were to collect exhaust emission data on four outboard motors, and to use these data with available population and usage information to estimate the national emissions impact of outboards. The emissions to be characterized included total hydrocarbons (FIA); CO, CO_2, NO, and hydrocarbons (NDIR); NO and NO_x (chemiluminescence); O_2(electrochemical); light hydrocarbons (gas chromatograph); and aldehydes by wet chemistry. These constituents are essentially the same as those measured for all gasoline-fueled engines operated under this contract, and particulate was not measured due to the complex configuration of the outboard exhaust systems. Emissions of Sulfur Oxides (SO_x) were calculated on the basis of fuel consumed, rather than being measured.

As part of the overall objective of gathering emissions data, it was necessary to design testing procedures which would simulate real-life operation as closely as possible. For outboards this task consisted not only of determining realistic speeds and loads, but also of developing the hardware necessary to measure exhaust gas concentrations both before and after the gases were bubbled through water. Anticipating the removal of some exhaust gas constituents by the water, it was planned originally to make analyses of the water before and after exhaust gases were bubbled through it as a cross-check on the gas analysis. This plan did not prove feasible because preliminary calculations based on changes in exhaust constituents showed that relatively small changes would be occurring in the water phase, requiring instrumentation more sensitive than that available in order to collect quantitative data.

III. INSTRUMENTATION, METHODS, AND CALCULATION TECHNIQUES

Several aspects of this study make it something of a departure from more routine emissions measurements; namely, the fact that the motors tested were of 2-stroke design (2-strokes dominate the field), that they had rather complicated exhaust systems designed for underwater discharge, and that operation at the air/water interface meant that their exhaust products might affect both phases. Three parts of the technical undertaking will be discussed in this section, and the fourth (impact analysis) will be discussed in section V.

A. Instrumentation and Sampling System

In general terms, the analysis instruments used on outboards and treatment of the gas samples conformed to SAE Recommended Practice J254. The exceptions were (1) use of a chemiluminescent NO-NO_x analyzer in addition to the NDIR NO analyzer, and (2) special treatment of some samples which consisted of bubbling them through water before analysis. As an introduction to the measurement systems used on the subject work, Figures 1 through 8 are presented. Figure 1 is an overall view showing the Johnson and Mercury outboards on dynamometer stands, the exhaust/water contact system, and the emissions instrumentation for CO, CO_2, NDIR NO, NDIR hydrocarbons and chemiluminescent NO_x and NO analysis. Figure 2 shows more detail of the engines and water contact system, and the wet chemistry sampling system and the FIA detector/oven assembly are shown at left. Figure 3 is a more detailed view of the sampling train described above, showing the FIA hydrocarbon analyzer's remote control systems at upper right and the 4-channel recorder at right center. Figure 4 shows the FIA oven and the wet chemistry system in more detail.

Figure 5 shows the operator's control panel for the Johnson 4R71 tests and the two large flowmeters (bottom center) used to measure water flow to the exhaust/water contact system. The contact system itself, which can be referred to as the "bubbling tank", consisted primarily of the plexiglass cylinder shown behind the control panel. Figure 6 shows more detail of the Johnson 4R71 engine tested, the dynamometer and the stroboscopic tachometer. Figure 7 is a detailed view of the bubbling tank, showing the internal float and level control system, wall and gasket construction, and typical bubbles moving through the tank. Figure 8 shows the Mercury 650 on the test stand undergoing emissions tests.

Figure 9 shows the new FIA oven/detector used for tests on the Chrysler 35 hp and OMC 9.5 hp engines, which also held the aldehyde sampling apparatus, as shown in Figure 10. The control panel used for these last two engines is shown in Figure 11 along with the Chrysler engine mounted on the test stand, and Figure 12 documents the test stand installation of the OMC 9.5.

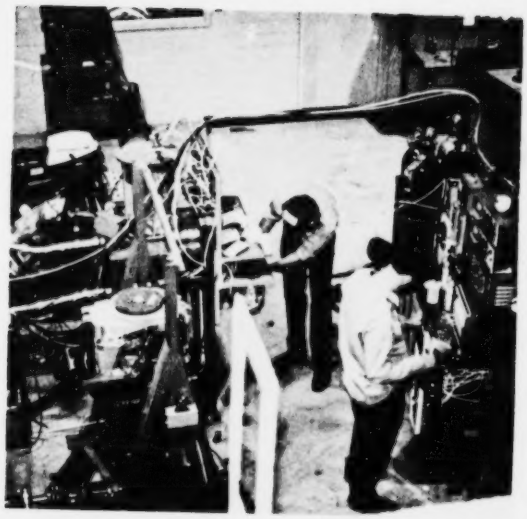

Figure 1. Overall View of Outboard Motor Test Stands and Emissions Measurement Equipment

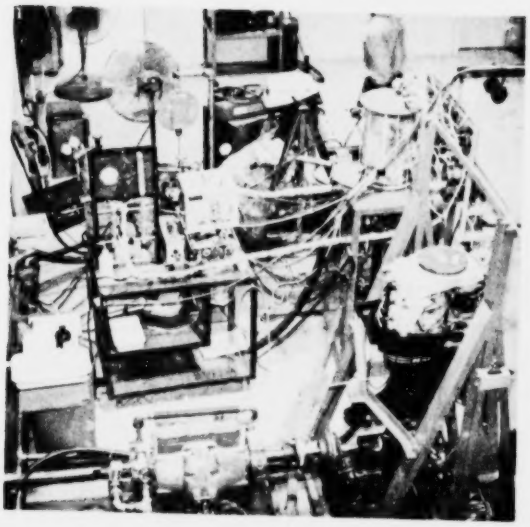

Figure 2. Overall View of Outboard Motors, FIA Oven/Detector, and Wet Chemistry Sampling System

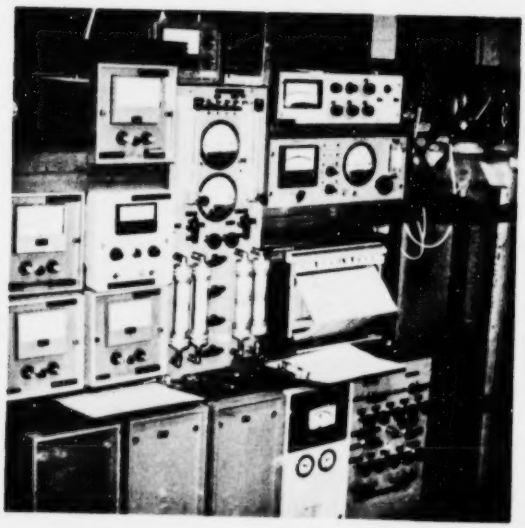

Figure 3. Detailed View of Analytical Instruments

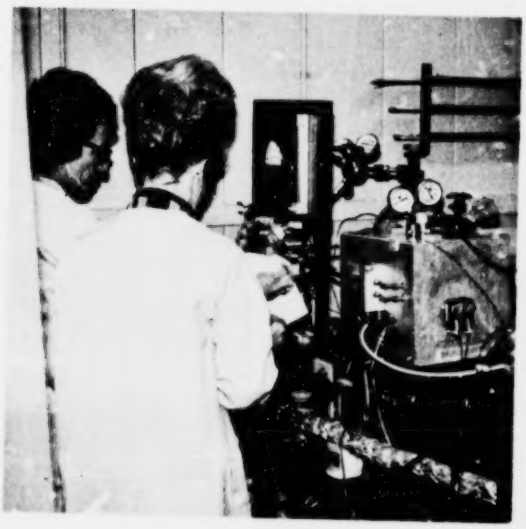

Figure 4. Detailed view of FIA Oven/Detector Unit and Wet Chemistry System Used for OMC 4 hp and Mercury 65 hp Engines

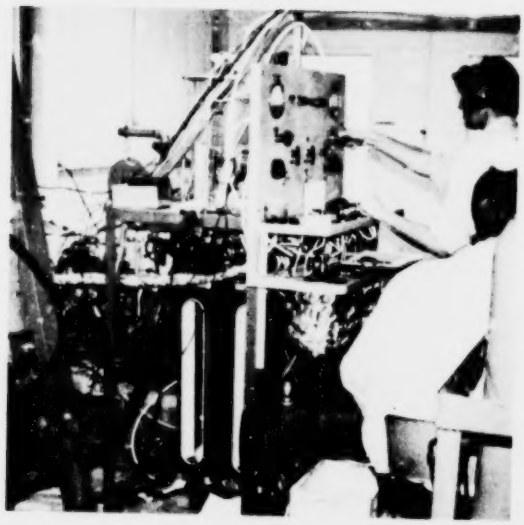

Figure 5. Operator's Control Panel for Johnson 4R71 Outboard Tests

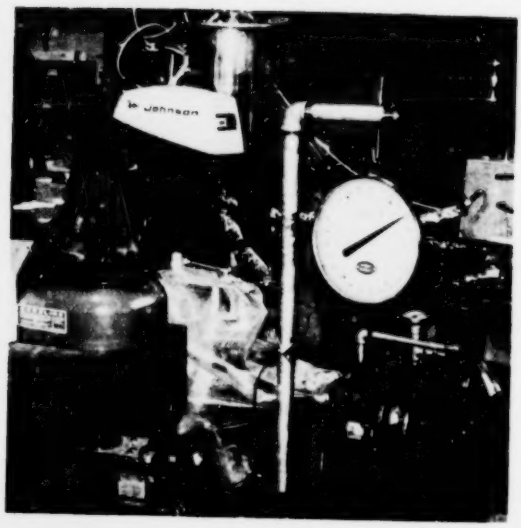

Figure 6. Johnson 4R71 Engine Under Test, Dynamometer, and Stroboscopic Tachometer

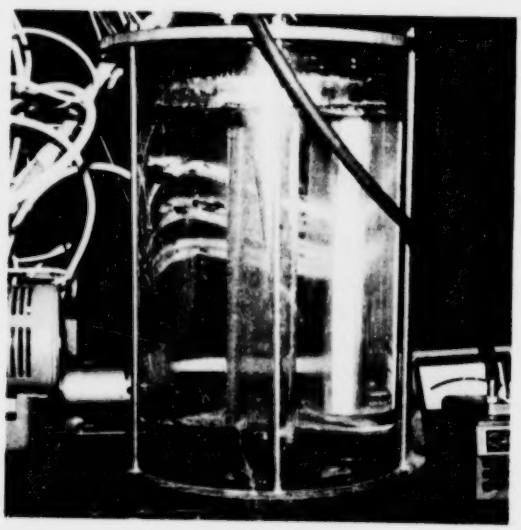

Figure 7. Detail of Exhaust/Water Contact System or "Bubbling Tank"

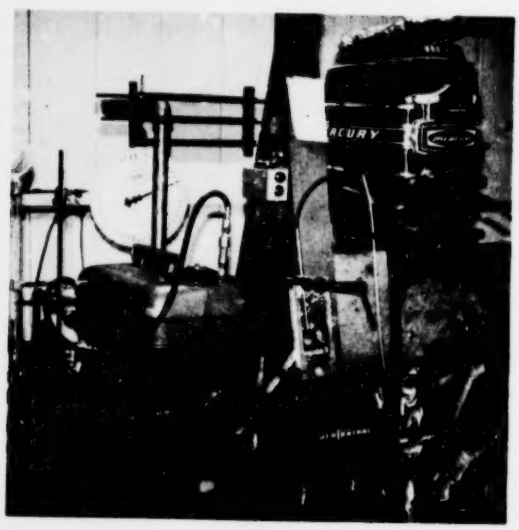

Figure 8. Front View of Mercury 650 Outboard Undergoing Emissions Tests

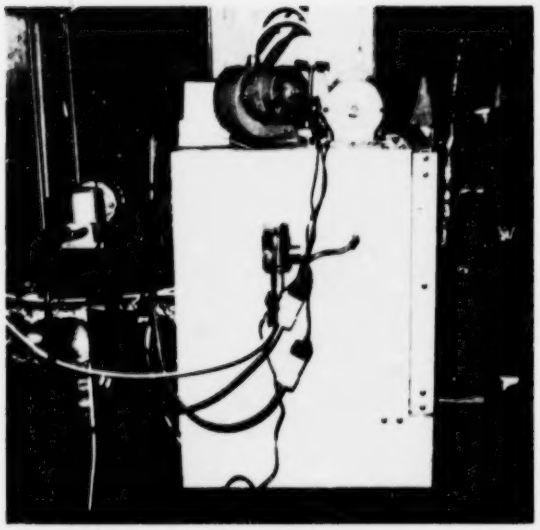

Figure 9. FIA Oven/Detector Unit Used for Tests on Chrysler 35 hp and OMC 9.5 hp Outboard Motors

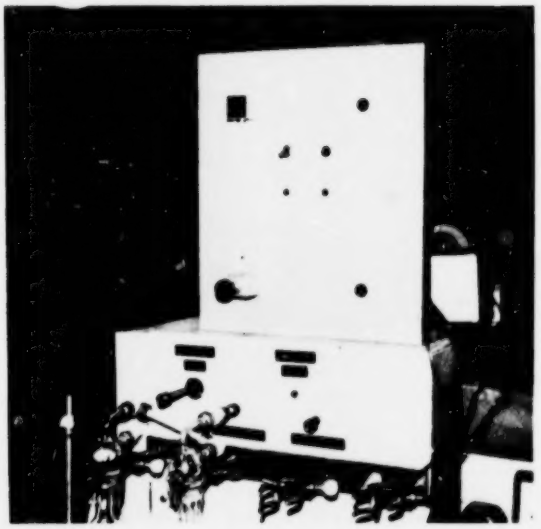

Figure 10. Aldehyde Sampling Apparatus Mounted on FIA Oven/ Detector

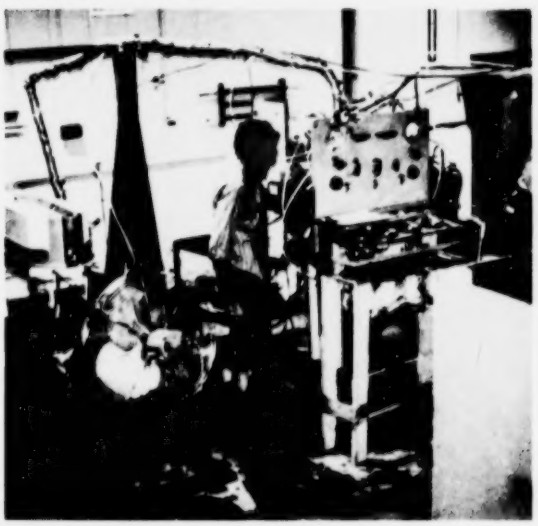

Figure 11. Control Panel Used for Tests on Chrysler 35 hp (shown) and OMC 9.5 hp Outboard Motors

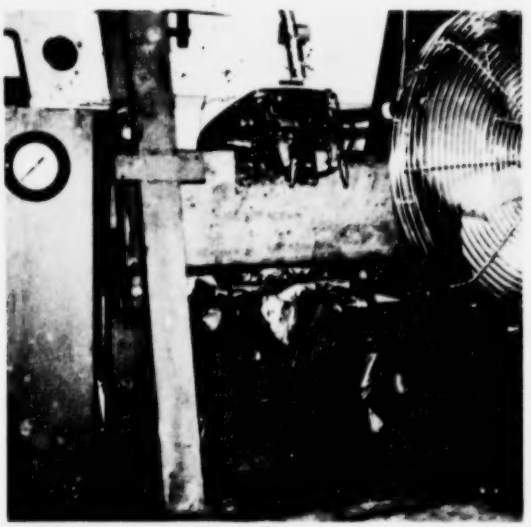

Figure 12. OMC (Johnson) 9.5 hp Engine Mounted on Test Stand

The photographs just described give some idea of the physical appearance of the system, but to really understand it the schematic given in Figure 13 is more helpful. The complexity in evidence was not called for in the original design, but various controls became necessary in the course of development. Raw exhaust entered the system and immediately went through a flask to remove entrained water. Exiting this first trap, a relief valve was provided to prevent contamination of the system while measurements were not being taken. The flow was split three ways following the valve, one each for the FIA, the wet chemistry system, and the remaining analyses. The configuration just mentioned, with direct samples to all analyzers, was used to obtain raw exhaust emission concentrations. To examine the effects of water scrubbing, the flow-switching valves were turned to force all the sample through the bubbling tank, and then the flow was again split three ways for analysis. Sample lines between the first water trap and the FIA and between this same trap and the wet chemistry analysis were heated to prevent condensation of moisture, but the remaining lines were at room temperature (except in the water traps).

The only major non-commercial piece of equipment used was the bubbling tank. Its wall was 12 inch O.D. by 1/4 inch wall plexiglass tubing, 18 inches in height, and the divider was 1/4 inch plexiglass sheet 15 inches in height. The top and bottom were made of 1/2 inch stainless steel plate, faced off and finished on the inside, and top and bottom gaskets were made of 1/8 inch Viton sheet. The float was made of thin-gauge aluminum, and the linkage to the float valve was made of stainless steel rod and sheet.

To allow sampling of the water which was used for exhaust scrubbing, valves were included in the system just prior to the water flowmeters and just downstream of the bubbling tank. It was later determined that no satisfactory results could be determined by water analysis using available instrumentation, so the sampling valves were not used.

In normal operation, those parts of the system which are most vulnerable to leaks, including the bubbling tank, were held under positive pressure. The tank head pressure was held at 65 inches of water, gage, for all the engines except the OMC 9.5 hp because gas and water flows could be kept steady at that condition. The pressure used for the OMC 9.5 was 50 inches of water, gage. The gas flowrate through the contact tank was about 11 liters per minute, which resulted in a purging time for the tank headspace of about 15 seconds. The tank water level control was installed to promote better purging of the tank by running the water level closer to the top of the tank without risk of getting water in the sample lines. The water flow rate through the tank was held at 25.0 liters per minute for the Johnson 4R71 and at 49.4 liters per minute for all the other engines except during "special" tests on the Mercury 650. The special tests were performed to determine the effects of water/exhaust gas ratio, bubble size, and water turbulence on removal of soluble or condensable exhaust

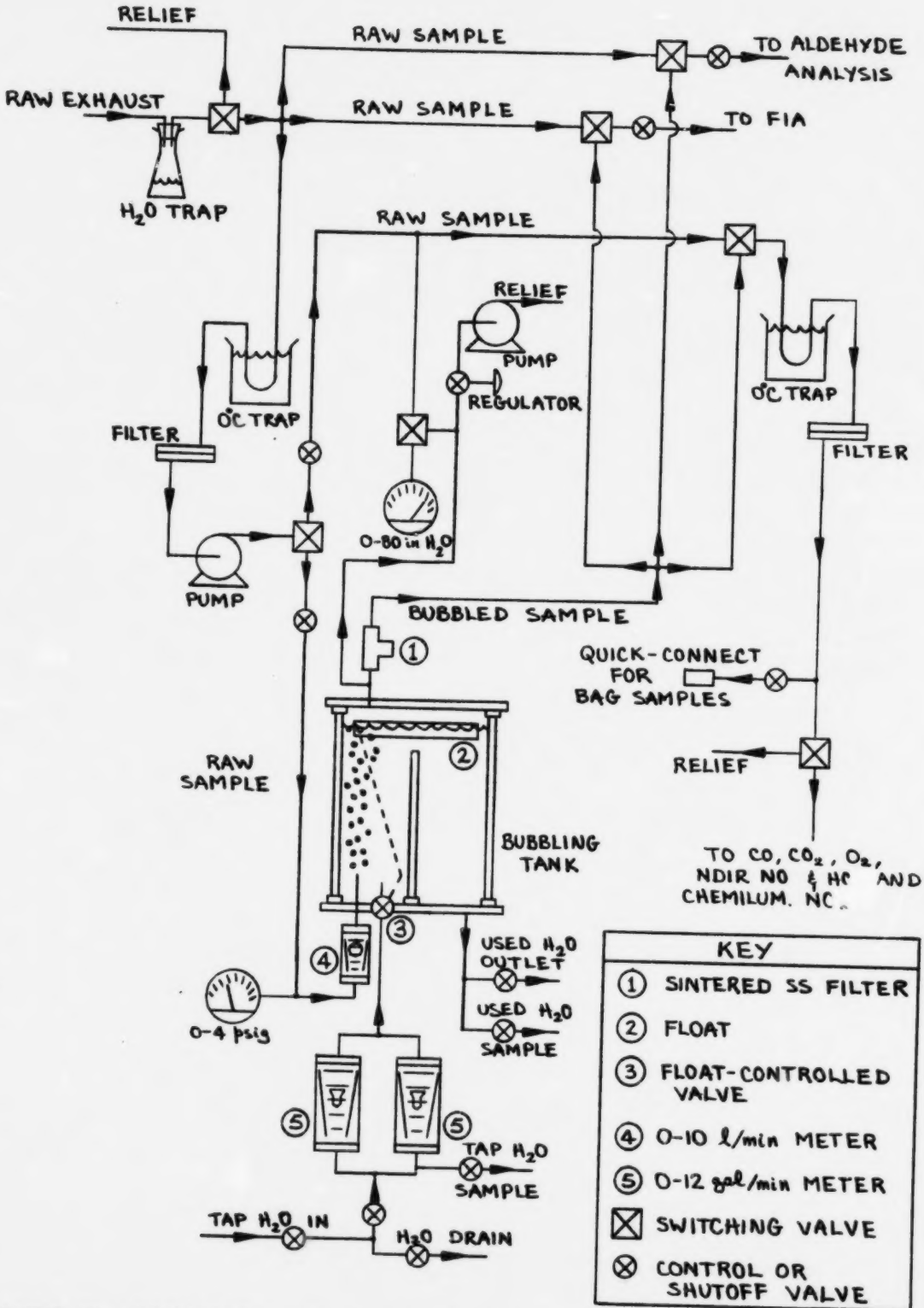

FIGURE 13. SCHEMATIC OF EXHAUST SAMPLING AND WATER CONTACT SYSTEMS USED FOR OUTBOARD MOTOR TESTS

constituents by the water, and they will be described in more detail in section IV. The water/exhaust gas ratios used were dictated by available water flow measurement instrumentation, practical sample flow rates, and economy considerations rather than representation of the real situation.

B. Test Procedures and Methods

For outboard motors, load (or power output) is a function of crankshaft speed, size and weight of boat being pushed, propeller characteristics, and other variables. If it can be established, however, that the engine is running at its "rated" rpm at wide-open throttle, then power output at lower speeds can be approximated by the relationship

$$\text{power output} = K N^x$$

where x ranges from something over 2 to perhaps 3, depending on hull design, matching of motor and boat, and surface speed. The quantity x is about 2.4[1] or 2.5 for planing-hull pleasure boats, and approaches 3 for displacement hull operation at low speed. The constant K is evaluated for a given boat/motor combination once x has been established by rearranging the above equation and evaluating K at rated speed and power:

$$K = \frac{\text{Maximum rated power}}{(\text{rated speed, rpm})^x}$$

Using this analysis for the four outboards tested during this project yielded run conditions by mode as given in Table 1.

TABLE 1. SPEED AND LOAD CONDITIONS USED FOR OUTBOARD TESTS

	Calculated Crankshaft Horsepower/Rpm in Modes by Engine				
Mode	OMC 4 hp x = 3	OMC 9.5 hp x = 2.5	Chrysler 35 hp x = 2.5	Chrysler 35 hp x = 3	Mercury 65 hp x = 2.5
1	4.00/4500	9.50/4500	35.0/5000	35.0/5000	65.0/5200
2	2.81/4000	7.08/4000	20.0/4000	17.9/4000	53.2/4800
3	1.19/3000	3.45/3000	9.8/3000	7.6/3000	33.7/4000
4	0.35/2000	1.25/2000	3.5/2000	2.2/2000	14.9/2890
5	0.09/1250	0.22/1000	0.6/1000	0.3/1000	6.0/2000
6	Idle(1050)	Idle (700)	Idle(1100)	Idle(1100)	1.1/1000
7	--	--	--	--	Idle(800)

The Chrysler 35 hp engine was run as if 5000 rpm were its rated speed because the engine was not very stable at its actual rated speed of 4750 rpm. The Johnson 4R71 was run at 1250 rpm instead of 1000 rpm in mode 5, and the Mercury 650 was run at 2890 rpm instead of 3000 rpm in mode 4,

both also due to instability at the "standard" speeds. Another way of arriving at intermediate-speed power output, where maximum power, rated speed and "x" are known, is to linearize the power equation by taking its logarithm or to plot it on full logarithmic graph paper as has been done for Figure 14. The graph agrees very well with Table 1, except for the Chrysler 35 hp engine, which starts out at its actual rated speed of 4750 rpm in Figure 14. Power points for the Chrysler were calculated on both 2.5 and 3rd order curves, and two (of a total of seven) runs were made using the latter to determine whether or not emissions would change significantly from those recorded using the 2.5 order points.

The test modes listed in Table 1 were generally run in top-to-bottom order, but enough runs were made in the opposite order to determine that the sequence was not significant. After each speed/power condition was established, emissions were allowed to stabilize (up to 5 minutes required at times), and raw emissions values were recorded and noted on on the chart readout. Following the initial reading, the sample flow was diverted through the bubbling tank, and another set of emissions numbers was recorded and marked on the chart. If, for instance, Mode 1 was the speed/power condition being run, Mode 1A would designate emissions measured after water scrubbing. The values for the "A" mode having been recorded, flow was switched back to the raw exhaust system, and another set of values was recorded. In other words, the sequence was; 1, 1A, 1, 2, 2A, 2, ..., etc. For the results given in this report, modes listed without the "A" designation are averages of raw exhaust concentrations measured before and after the "bubbled sample" concentrations, all while the engine was being held at constant speed and load. This procedure helped to minimize the effect of "drifting" of emissions values during each mode.

Engine power output was recorded for each mode at the propeller shaft, and these figures were generally as expected considering ambient conditions and frictional losses in the drive trains. The average values are tabulated in Table 2 rather than being included in the Appendix. Variations in engine speed were very minor from run to run, so rpm data will not be included in the Appendix, either. Fuel consumption was measured while emissions were being measured by recording time required for the engines to consume a predetermined volume of fuel. Fuel temperature was recorded, and density measurements (separate for each batch of fuel) were corrected to that temperature before performing the volume-to-mass conversion. It should be noted that the gasoline used conformed to Federal emissions test fuel specifications[2], similar to the standard fuel called Indolene 30. Gasoline-oil mixtures conformed to manufacturer's specifications, meaning that the correct brand of TCW-type was used in each engine at a 50:1 gasoline:oil ratio.

C. Calculations Leading to Mass Emissions Values

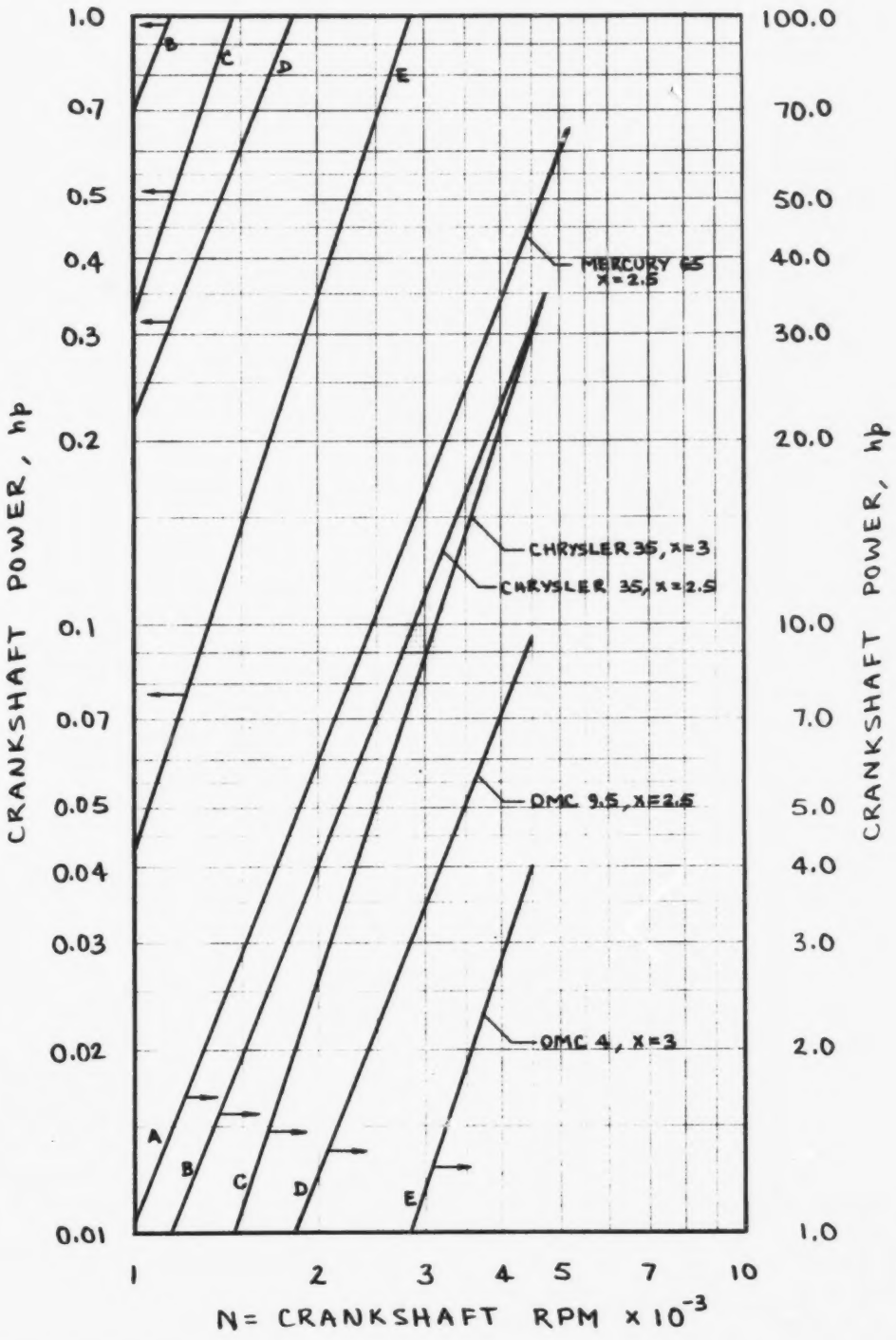

FIGURE 14. BOAT LOADING CURVES FOR OUTBOARD MOTORS BASED ON THE FORMULA $hp = KN^x$

Emission concentration data in this report, both in the Appendixes and in text, are on a "wet" basis; that is, they have been adjusted back to

TABLE 2. AVERAGE POWER OUTPUT OBSERVED DURING OUTBOARD TESTS

Mode	Average Observed Propshaft Horsepower/Rpm in Modes by Engine				
	OMC 4 hp x = 3	OMC 9.5 hp x = 2.5	Chrysler 35 hp x = 2.5	Chrysler 35 hp x = 3	Mercury 65 hp x = 2.5
1	2.73/4500	7.29/4500	28.4/5000	28.4/5000	53.4/5200
2	1.74/4000	5.34/4000	16.1/4000	14.3/4000	45.6/4800
3	0.75/3000	2.59/3000	7.9/3000	6.1/3000	29.2/4000
4	0.23/2000	0.95/2000	2.9/2000	1.8/2000	13.0/2890
5	0.05/1250	0.17/1000	0.5/1000	0.2/1000	5.2/2000
6	Idle/(1050)	Idle/(700)	Idle/(1000)	Idle/(1100)	0.9/1000
7	--	--	--	--	Idle/(800)

actual values before intake air humidity and water of combustion were removed. This step was not necessary only for FIA hydrocarbons and aldehydes, both of which were measured "wet". Conventional equations were employed in converting raw concentrations from a "dry" to "wet" basis, but they were inadequate for "bubbled" concentration data. For the bubbled gases, it was assumed that the concentration of water in the exhaust upon leaving the water contact system was the same as that of saturated air at the temperature of the water. This temperature varied overall from about 65° F to 80° F, and the corresponding assumed water content of the bubbled gases varied accordingly. Calculations required to extrapolate the mass emissions to national impact will be explained in section V.

In order to calculate mass-based emissions from the concentrations, use of standard carbon balance techniques for the raw exhaust gave good results, but a problem arose in computing mass emissions after water contact because the amount of exhaust gained or lost during bubbling was not known accurately. It was decided that a nitrogen balance would be used, since it seemed reasonable that little or no change in nitrogen mass flow would occur in the bubbling system.

Nitrogen concentrations were determined for both raw and bubbled exhaust by subtracting mole percentages of measurable or calculable constituents from 100.0 percent. Since the assumption made is that nitrogen through the system is conserved, the fraction of the total raw exhaust which comes out as bubbled exhaust can be calculated by the relation

$$\frac{\text{raw concentration } N_2}{\text{bubbled concentration } N_2} = \frac{\left(\frac{\text{moles } N_2 \text{ in raw exhaust}}{100 \text{ moles raw exhaust}}\right)}{\left(\frac{\text{moles } N_2 \text{ in bubbled exhaust}}{100 \text{ moles bubbled exhaust}}\right)}$$

$$= \frac{\text{moles bubbled exhaust}}{\text{moles raw exhaust}}$$

The percent loss of each constituent, then, can be calculated by the relation

$$\% \text{ of X lost} = \frac{100\left[\text{raw X conc.} - \left(\frac{\text{raw } N_2 \text{ conc.}}{\text{bubbled } N_2 \text{ conc.}}\right)\left(\text{bubbled X conc.}\right)\right]}{\text{raw X conc.}}$$

and since these losses are for individual constituents, they can be construed as % losses by mass. This (fractional) loss in the water, multiplied by total mass emitted, becomes the mass rate at which each constituent is being emitted into the water. The remainder is the amount being emitted into the air and can be calculated as 100% minus the % of X lost. An additional refinement in these calculations has been made by correcting the observed losses during water contact of hydrocarbons, oxygen, and CO to a pressure of 1 atmosphere by Henry's law. The tank head pressure was maintained at 65 inches of water gage (50 inches for the OMC 9.5 hp engine), so the corrections to observed losses ranged from 0.873 to 0.910. The losses of CO_2 and NO_x were not corrected because Henry's law does not apply when molecular dissociation is involved. It should be stressed here that the results reported do not necessarily reflect conditions in the field, especially in the areas of water properties, water/exhaust gas contact ratio, and turbulence in the mixing region. It is probable, however, that effects such as those observed do occur to either a greater or lesser extent.

Note that all data which are reported in concentrations, including that in the Appendixes and the aldehyde and light hydrocarbon data given in the text, are reported on a wet basis, but that the "A" mode data (after bubbling) are not corrected to 1 atmosphere by Henry's law (concentration data only).

IV. RESULTS OF EMISSIONS TESTS

Emissions concentration data from which the results presented in this section were calculated are given in detail in the Appendixes, except for data on aldehydes and light hydrocarbons, which are summarized in text. Appendix A contains data on the Johnson 4 hp engine, Appendix B gives data on the Johnson 9.5 hp engine, Appendix C consists of data on the Chrysler 35 hp engine (including special tests), and Appendix D contains data on the Mercury 65 hp engine (including special tests). The special tests will be discussed in detail in subsections B and C.

A. Results of Tests Designed to Simulate Normal Operation

Following computations performed as described in section III. C., mass emissions for the four engines have been combined and appear as Table 3. Note that modes 1 through 6 are roughly comparable as to speed and percent load among the two OMC engines and the Chrysler, but that the extra mode (mode 2) on the Mercury means that mode 3 for the Mercury is comparable to mode 2 for the other engines (4000 rpm), etc. The data given for the Chrysler are from tests using power points based on a 2.5 order curve, and it should also be noted that the water:exhaust ratio was 2.25 for the OMC 4 hp engine and 4.45 for the others. In addition, the propeller in the bubbling tank which was used to generate additional turbulence during the special tests on the Mercury 650 (reported later) was "off" during regular tests on the Mercury 650 and the Johnson 4R71, and "on" during regular tests on the other two engines. The tube through which exhaust gases entered the bubbling tank was called a "bubbler", and the particular type used for the regular tests was made of 1/2 inch stainless steel tubing with the end welded shut, and four 1/16 inch holes drilled in its sides. This device was termed a "perforated" bubbler and was essentially the same for all the regular tests, except that it protruded 1 inch further into the tank for tests on the Chrysler 35 hp and Johnson 9.5 hp engines than it did for tests on the other two engines.

Table 3 contains data on raw emissions (as they left the engines) and the emissions which appeared to end up in the water. To obtain the emissions going into the air, it is necessary only to subtract the emissions remaining in the water from the raw emissions. This step will be performed in Section V, with certain assumptions regarding applicability of the various combinations of water:exhaust ratio and turbulence, so that emission factors can be developed separately for emissions into the atmosphere and the water.

The raw mass emission rates in Table 3 have been plotted as functions of crankshaft rpm in Figures 15, 16, 17, and 18. It is understood that engine power output was varying exponentially with crankshaft rpm. Figure 15 shows hydrocarbon emissions from the four engines, Figure 16 shows CO, Figure 17 shows CO_2, and Figure 18 depicts NO_x. It is not normal practice to devote much analysis to CO_2 emissions from land-based engines, but an

TABLE 3. TOTAL MASS EMISSIONS AND MASS EMISSIONS RETAINED IN WATER PHASE (EXPERIMENTALLY) FOR FOUR OUTBOARD MOTORS

		Raw Mass Emission Rate, g/hr				Loss in Water (Experimental), g/hr			
		Johns.	Johns.	Chrys.	Merc.	Johns.	Johns.	Chrys.	Merc.
Mode	Gas	4	9.5	35	65	4	9.5	35	65
1	HC	577	792	2880	6340	148	294	1460	2220
	CO	699	2140	9310	8910	64.0	79.9	384	260
	CO_2	2660	5830	13500	32800	857	2330	5300	14300
	NO_x	5.5	6.3	9.7	81.5	1.4	0.5	2.5	14.4
	O_2	1560	1970	5230	17700	-86.9	-71.8	-301	215
	H_2O	1480	4020	12300	19900	1210	3190	9800	16500
2	HC	324	813	1850	4660	97.8	351	686	1350
	CO	587	1690	5760	6170	104	83.2	319	270
	CO_2	1980	5350	9803	29200	723	2240	3910	13300
	NO_x	1.3	3.8	6.9	83.4	0.1	0.4	1.9	16.1
	O_2	1010	2040	3350	12500	60.4	-106	-152	-428
	H_2O	1110	3560	8300	16900	931	2800	6600	14300
3	HC	212	827	1550	2730	63.4	365	572	977
	CO	474	1520	4020	5030	51.7	71.5	115	177
	CO_2	1350	3790	6540	19000	426	1520	2730	7570
	NO_x	0.6	1.9	3.5	19.2	0.0	0.4	1.6	1.5
	O_2	565	2020	2830	6750	-36.1	28.9	-177	-299
	H_2O	806	2720	5650	11660	671	2120	4440	9920
4	HC	168	638	1040	2120	61.5	310	390	743
	CO	303	951	2310	4850	25.2	68.0	138	193
	CO_2	748	2180	4130	10300	294	867	998	3830
	NO_x	0.2	0.7	1.7	3.2	0.0	0.2	0.7	0.9
	O_2	378	1340	1880	5670	-22.4	43.2	-45.6	-89.5
	H_2O	507	1650	3440	7760	427	1280	2700	6590
5	HC	176	413	746	1980	54.0	200	286	552
	CO	275	472	1080	2890	24.2	45.1	80.5	6.3
	CO_2	464	885	1850	6480	124	342	772	2450
	NO_x	0.1	0.1	0.6	0.8	0.0	0.0	0.4	0.3
	O_2	343	769	1170	5000	-17.6	33.3	63.1	34.6
	H_2O	369	730	1600	4840	306	558	1230	4030
6	HC	198	402	1030	2170	64.0	190	378	537
	CO	242	365	1010	2590	22.0	31.0	73.6	116
	CO_2	373	662	1630	4300	100	261	666	1550
	NO_x	0.0	0.1	0.6	0.8	0.0	0.0	0.4	0.4
	O_2	358	729	1410	5750	-1.6	32.5	48.6	67.8
	H_2O	315	564	1480	3780	258	422	1100	3030
7	HC	--	--	--	1870	--	--	--	389
	CO	--	--	--	1610	--	--	--	70.4
	CO_2	--	--	--	2440	--	--	--	799
	NO_x	--	--	--	0.5	--	--	--	0.2
	O_2	--	--	--	5610	--	--	--	138
	H_2O	--	--	--	2350	--	--	--	1760

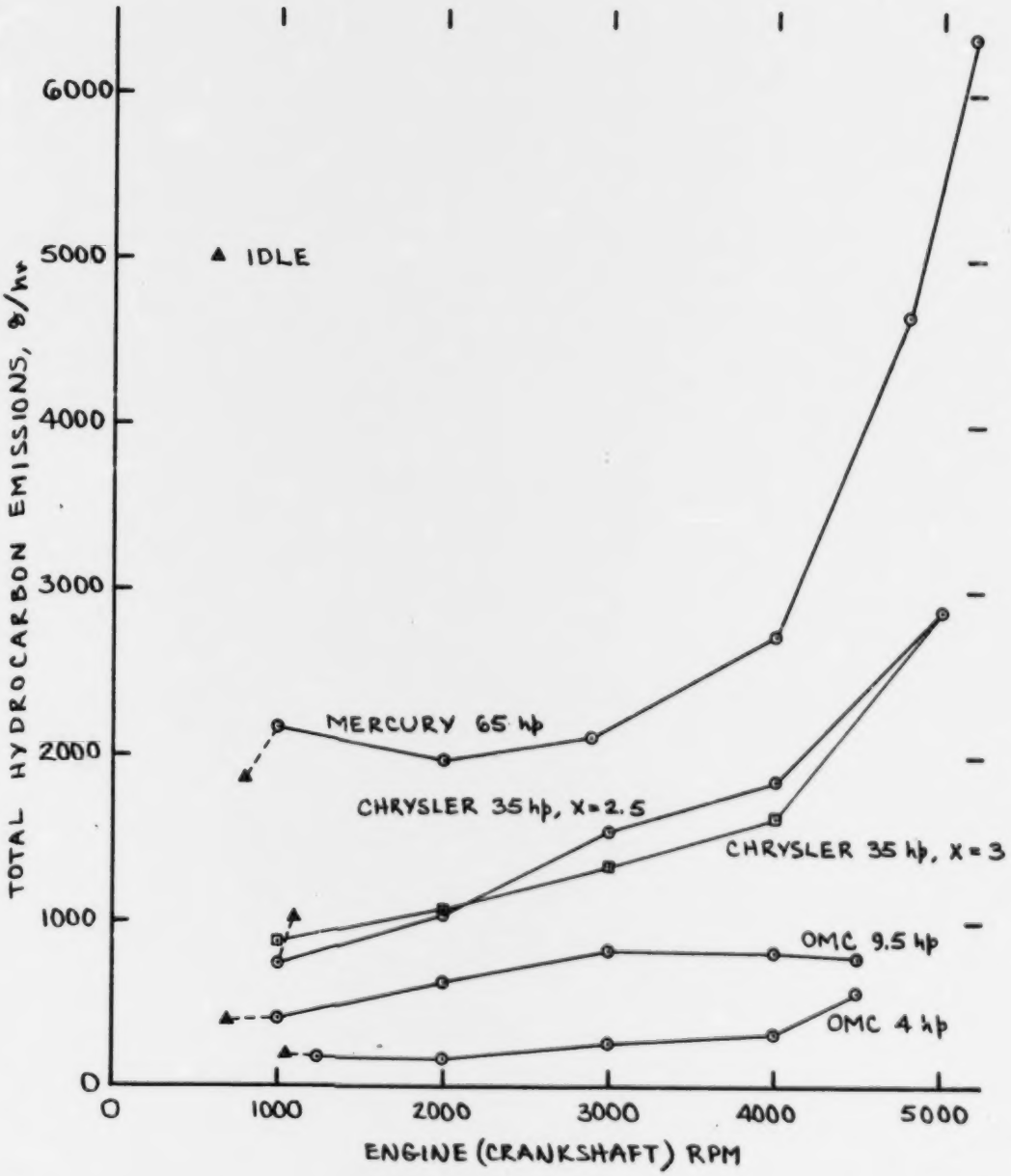

FIGURE 15. HYDROCARBON EMISSIONS FROM FOUR OUTBOARDS AS A FUNCTION OF CRANKSHAFT RPM WITH SIMULATED BOAT LOAD AS DESCRIBED IN TABLES 1 AND 2

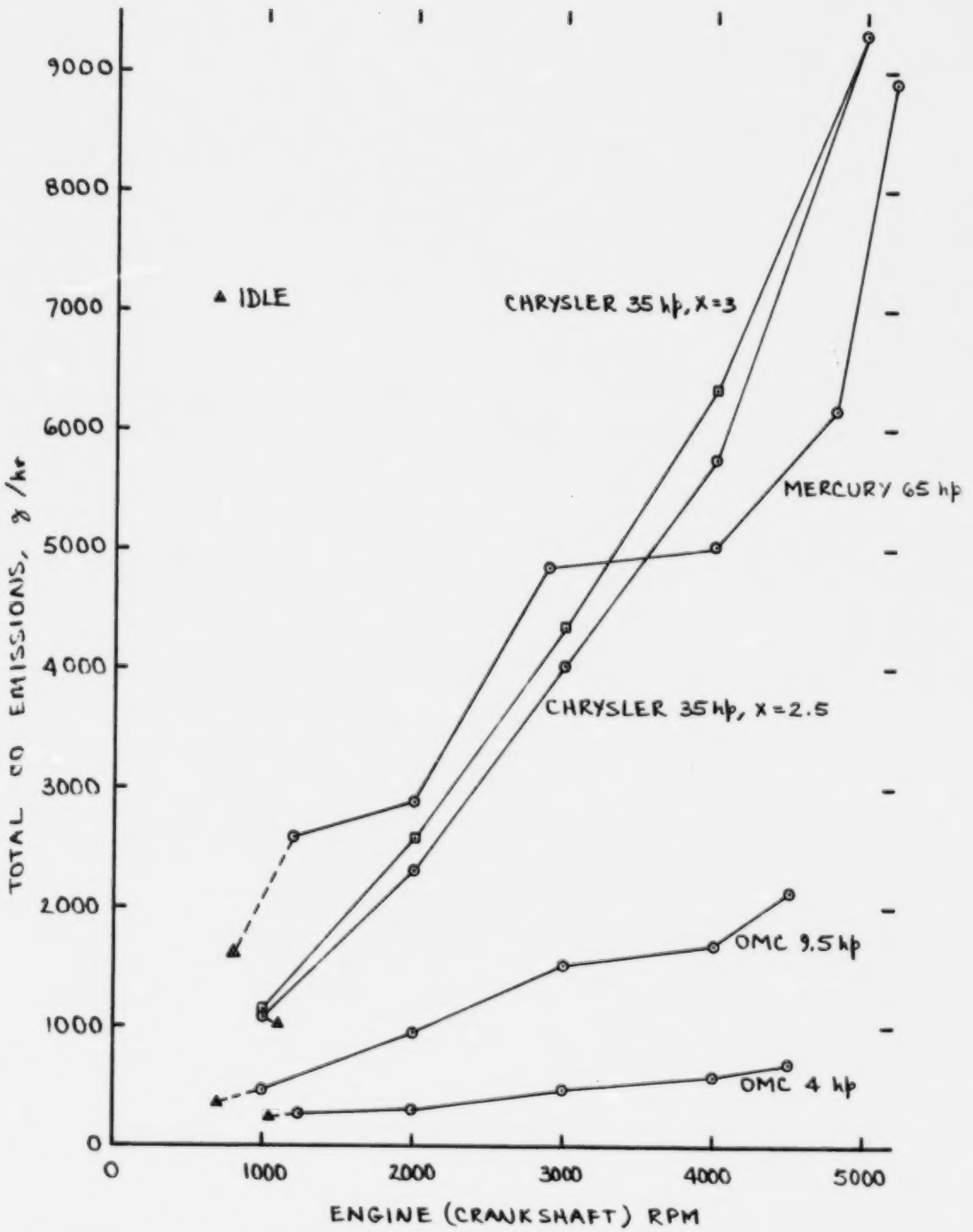

FIGURE 16. CARBON MONOXIDE EMISSIONS FROM FOUR OUTBOARD MOTORS AS A FUNCTION OF CRANKSHAFT RPM WITH SIMULATED BOAT LOAD AS DESCRIBED IN TABLES 1 AND 2

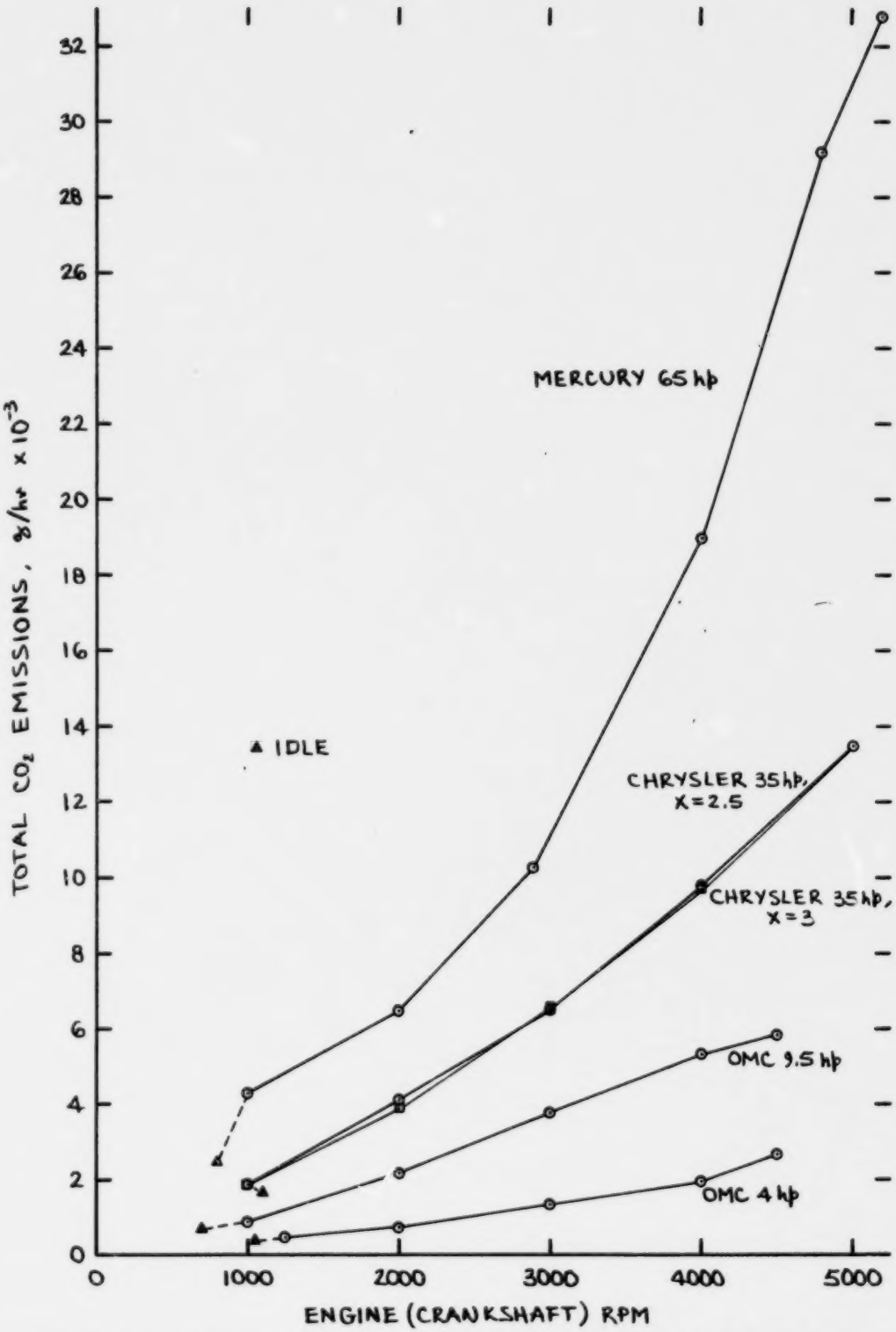

FIGURE 17. CARBON DIOXIDE EMISSIONS FROM FOUR OUTBOARD MOTORS AS A FUNCTION OF CRANKSHAFT RPM WITH SIMULATED BOAT LOAD AS DESCRIBED IN TABLES 1 AND 2

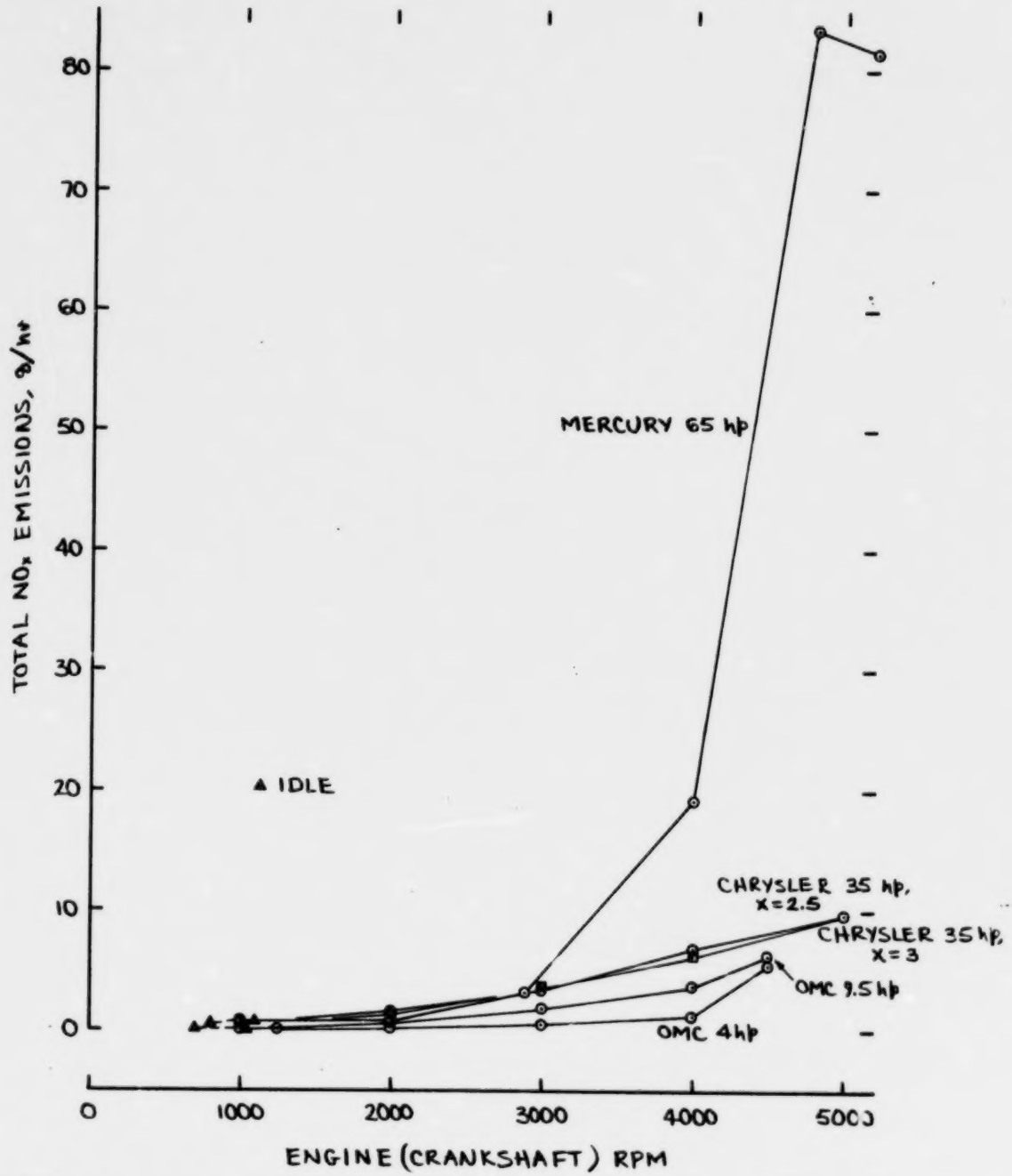

FIGURE 18. OXIDES OF NITROGEN EMISSIONS FROM FOUR OUTBOARD MOTORS AS A FUNCTION OF CRANKSHAFT RPM WITH SIMULATED BOAT LOAD AS DESCRIBED IN TABLES 1 AND 2

exception is being made for outboards because significant amounts of CO_2 are retained in the water phase, where CO_2 may be of greater importance. The mass emissions rates shown in Figures 15 through 18 reveal few real surprises, but several items are worthy of note. The general increases in emission rates with engine speed and load are to be expected, the only real exception being the small decrease in hydrocarbons from the OMC 9.5 hp engine above mid-speed. It is possible that the test engine was not typical in this respect because its fuel rate and power output were slightly lower than expected, also. Another expected trend was that the larger engines should produce more emissions by mass than the smaller engines, and the only major departure from this trend was the marked shift in CO emissions from the Mercury 65 hp engine above 3000 rpm (Figure 16). This shift shows a combustion change, which was also noted in Figures 17 (slightly) and 18 (markedly). For some reason the trapped charge was burned much more completely to CO_2 above 3000 rpm, resulting in higher cylinder pressure and temperature and the acceleration of NO_x shown in Figure 18. No dramatic change in hydrocarbons was noted because most of the hydrocarbons in the exhaust are due to untrapped air/fuel mixture, not partially-burned trapped mixture.

In addition to the gaseous emissions measured on a continuous basis, light hydrocarbons were measured on bag samples by gas chromatograph and aldehydes were measured by wet chemistry. The light hydrocarbon data are summarized in Table 5 in terms of concentrations on a wet basis, but the "A" mode data (after water scrubbing) have not been corrected to atmospheric pressure by Henry's Law. The same comments apply to the data on formaldehyde (HCHO) and total aliphatic aldehyde (RCHO) concentrations shown in Table 4. Of the light hydrocarbons, the only compound absorbed strongly by the water was acetylene, although several of the others would show smaller losses in the water if mass-based computations were made. Both HCHO and RCHO (which includes formaldehyde, of course) showed large losses in the water phase, as expected. All the light hydrocarbon and aldehyde emissions could be computed on a mass rate basis if it became desireable for some reason, but such a detailed analysis is not considered necessary for this initial study. The results given in this subsection will be used in section V to estimate national outboard emissions impact.

B. Results of Tests Designed to Investigate the Water Scrubbing Process

Having analyzed several outboard motor emissions tests, it seemed that several parameters and variables of the particular measurement system used may have had some effect on the changes in exhaust gas composition during water contact. Some of these items are water temperature, absolute pressure at which the contact system is maintained, pH of the bubbling water as it enters the tank, bubble residence time in the tank,

(H_2O/exhaust) ratio, bubble size, and turbulence in the tank. Although no assertion is made that the system used for the subject tests represents the real situation (indeed, in some instances it definitely does not), at least the variations in most of the properties mentioned were either minimized or carefully controlled. Throughout the regular tests on all the outboards and the special tests on the Mercury 650, the contact water temperature was relatively constant (nominal 66°F for the OMC 4 hp & Mercury 65 hp engines, nominal 77°F for the other two); the tank head pressure was held at 65 inches of water gage for all the engines except the OMC 9.5, for which it was 50 inches (so absolute pressure varied only with atmospheric pressure and this variation was corrected for by Henry's Law, where applicable); the incoming water pH stayed between 7.2 and 7.4; and bubble residence time (as a function of water depth) was held essentially constant. Provisions were made for controlled variation of (H_2O/exhaust) ratio, bubble size, and turbulence, although these variations were not necessarily independent of one another. The (H_2O/exhaust) ratio was changed by holding the gas flow constant and varying the water flow, to yield ratios by volume (70°F and 1 atm.) of 2.25, 4.45, and 6.00. The bubble size was varied by changing "bubbler" configuration and the turbulence was varied both by changing the water flow and by switching the propeller off and on.

TABLE 4. AVERAGE CONCENTRATIONS OF FORMALDEHYDE (HCHO) AND TOTAL ALIPHATIC ALDEHYDES (RCHO) IN THE EXHAUSTS OF FOUR OUTBOARD MOTORS BEFORE AND AFTER WATER SCRUBBING

Mode	OMC 4 hp	OMC 9.5 hp	Chrys. 35 hp	Merc. 65 hp	OMC 4 hp	OMC 9.5	Chrys. 35 hp	Merc. 65 hp
1	31	9.3	28	28	70	25	67	72
1A	18	7.5	19	15	31	14	31	36
2	32	14	17	38	52	38	52	58
2A	18	5.9	15	16	35	14	28	58
3	47	12	29	16	82	40	70	44
3A	28	6.2	18	12	42	16	32	22
4	46	38	53	27	92	66	138	55
4A	21	9.0	23	10	37	15	47	19
5	31	16	74	14	61	42	154	40
5A	21	7.2	54	10	36	16	80	24
6	20	14	125	30	64	44	125	53
6A	16	11	28	15	35	21	52	53
7	-	-	-	21	-	-	-	44
7A	-	-	-	19	-	-	-	44

TABLE 5. AVERAGE CONCENTRATIONS OF LIGHT HYDROCARBONS IN THE EXHAUSTS OF FOUR OUTBOARD MOTORS BEFORE/AFTER WATER SCRUBBING

Mode	Engine	Concentrations of Light Hydrocarbons by Species, ppm						
		CH_4	C_2H_6	C_2H_4	C_3H_8	C_2H_2	C_3H_6	C_4H_{10}
1	OMC 4	122/136	42/48	210/230	13/17	102/59	- / -	304/317
	OMC 9.5	369/421	46/71	213/231	4/13	161/88	162/169	169/243
	Chrys. 35	485/637	43/48	210/220	13/14	203/111	129/122	183/239
	Merc. 65	331/336	64/59	221/215	8/6	118/55	201/194	396/395
2	OMC 4	309/408	172/205	506/628	30/32	106/92	- / -	268/320
	OMC 9.5	497/435	56/111	190/334	7/4	72/50	149/348	101/261
	Chrys. 35	717/807	61/71	254/265	10/10	339/164	172/176	155/179
	Merc. 65	294/291	64/61	221/214	6/5	102/39	218/186	370/380
3	OMC 4	462/462	216/202	620/624	58/24	262/116	- / -	335/307
	OMC 9.5	759/890	214/242	658/719	25/21	306/137	501/519	259/340
	Chrys. 35	1241/1313	172/181	578/571	6/11	562/286	411/392	171/196
	Merc. 65	323/311	54/70	184/160	6/4	131/44	122/111	278/275
4	OMC 4	439/442	128/140	447/418	20/18	314/213	- / -	334/248
	OMC 9.5	1047/1307	194/228	650/698	29/26	732/518	491/493	320/359
	Chrys. 35	1183/1369	197/209	678/665	15/13	615/263	439/428	187/168
	Merc. 65	1160/1390	46/72	293/315	7/8	808/417	160/73	419/512
5	OMC 4	769/1050	111/134	429/524	36/62	888/578	- / -	400/614
	OMC 9.5	2260/2142	170/169	711/672	45/36	1777/807	516/400	661/601
	Chrys. 35	1810/1872	181/190	669/663	23/35	1370/611	370/419	399/514
	Merc. 65	1590/1570	81/73	344/322	9/9	1150/631	194/162	563/513
6	OMC 4	976/1010	118/114	542/478	39/25	1024/690	- / -	635/558
	OMC 9.5	1725/2317	168/224	673/840	29/40	1452/1033	370/413	457/649
	Chrys. 35	2187/2193	246/268	804/940	37/46	1483/822	553/455	563/684
	Merc. 65	1890/2080	117/125	491/483	11/15	1370/648	218/234	578/721
7	Merc. 65	2160/2220	118/121	574/528	19/20	1520/591	292/288	967/1030

Figure 19 is a detailed view of the bottom of the bubbling tank in the general configuration used for the special tests. For the regular tests, the propeller was not yet in place, and the "bubbler" (the pipe protruding upward through the tank bottom to the left of the propeller) was shorter and made a little differently. Regarding the details of the design, the propeller was a model airplane propeller shortened to 2 inches in diameter and having a pitch of 2.125 inches, mounted 1 inch above the bottom of the tank and 1 1/2 inches from the bubbler on centers. In operation, it was rotated at about 1650 rpm by an electric motor.

The bubbler shown in Figure 19 was called the "sintered" bubbler, because it was made from a sintered stainless steel filter element affixed to a piece of tubing with epoxy (the axial center of the element was 2 inches from the tank bottom). The second design (shown later) was called the "perforated" bubbler and was made of a piece of tubing with the end welded shut and 4 small holes drilled in its wall at a point 2 inches from the tank bottom. The third bubbler (also shown later) was just a length of tubing with an open end 2 inches from the bottom of the tank. The sintered bubbler generated the smallest bubbles, the perforated one generated intermediate-size bubbles, and the "tube" (open-ended) bubbler generated the largest bubbles. The tube and sintered bubblers were used only during the special tests on the Mercury 650, but the perforated bubbler was used for the regular tests on the OMC 9.5 and Chrysler 35 engines, and the bubbler used for regular tests on the other two engines was similar to the perforated unit except that the holes were less than 1/2 inch from the tank bottom.

Continuing with descriptions, Figure 20 shows the tube (open-ended) bubbler installed in the tank. This figure also shows typical bubbles generated by the tube bubbler with the propeller off and at the lowest water flow rate (H_2O/exhaust ratio = 2.25). Figure 21 shows bubbles generated by the perforated bubbler at the same conditions, and although the photograph is not very clear the bubbles seem about the same as those in Figure 20. Figure 22 shows bubbles generated by the sintered bubbler, again with the lowest water flow and the propeller off, and the difference between this bubbler and the other two is quite apparent.

Figures 23 and 24 were taken with the tube bubbler in place, and with the lowest water flow rate, but the propeller was "off" in Figure 23 and "on" in Figure 24. Figures 23 and 24 were taken by available light with the camera hand-held, while the earlier bubbling tank photos were taken with an electronic flash. The earlier photos have better depth of field and detail, but the latter (with a shutter speed of 1/2 second or so) show what the bubbles were doing much more clearly. The effect of the propeller on turbulence in the mixing region is clearly in evidence in Figure 24.

Figures 25 and 26 were taken with the perforated bubbler in place and back lighting using an incandescent lamp. The camera was again hand-held and a long exposure was used. The water/exhaust ratio in use was 4.45,

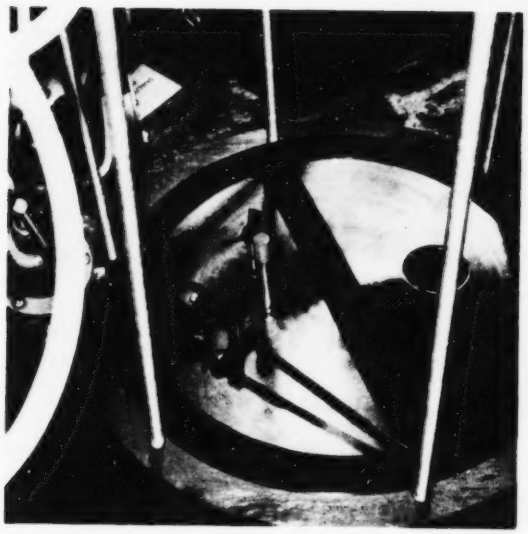

Figure 19. Close-up Detail of Tank Bottom with Propeller and Sintered Bubbler Installed

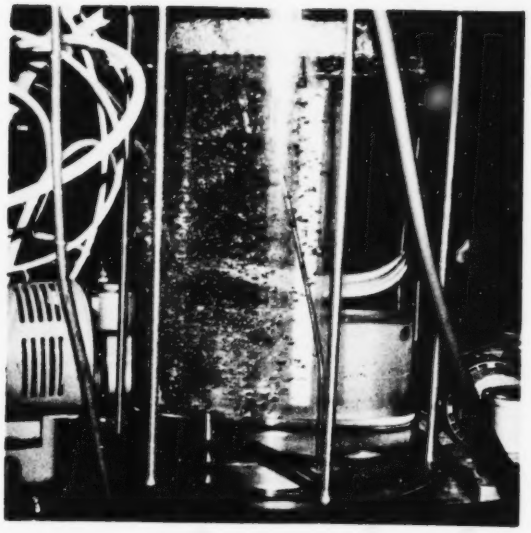

Figure 20. Tube Bubbler With Lowest Water Flow Rate and Propeller Off

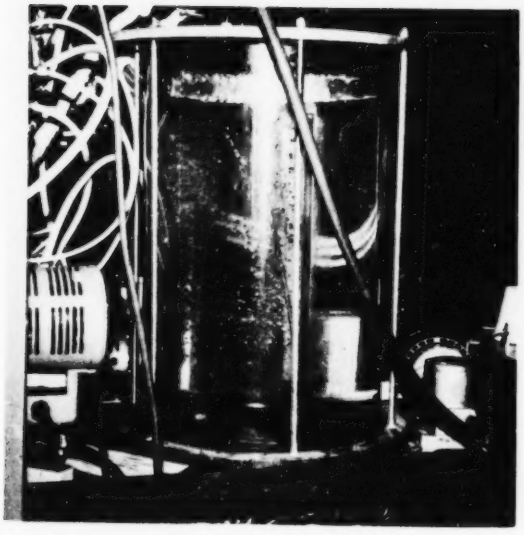

Figure 21. Perforated Bubbler with Lowest Water Flow Rate and Propeller Off

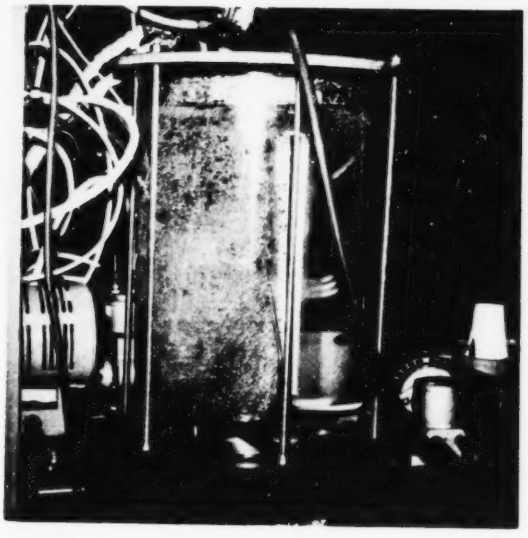

Figure 22. Sintered Bubbler with Lowest Water Flow Rate and Propeller Off

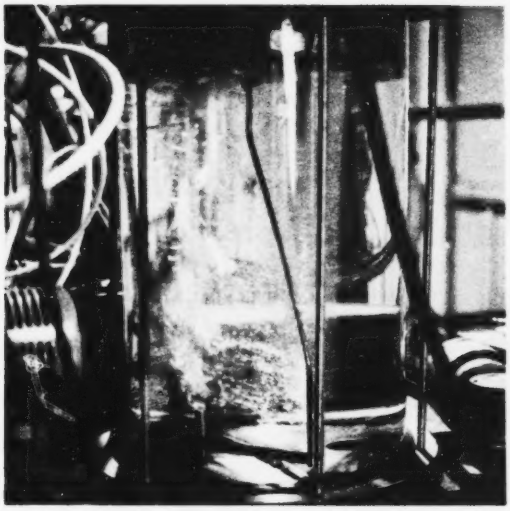

Figure 23. Tube Bubbler with Lowest Water Flow Rate and Propeller Off

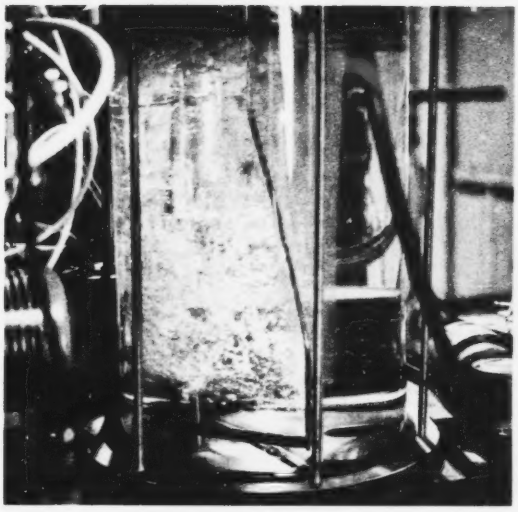

Figure 24. Tube Bubbler with Lowest Water Flow Rate and Propeller On

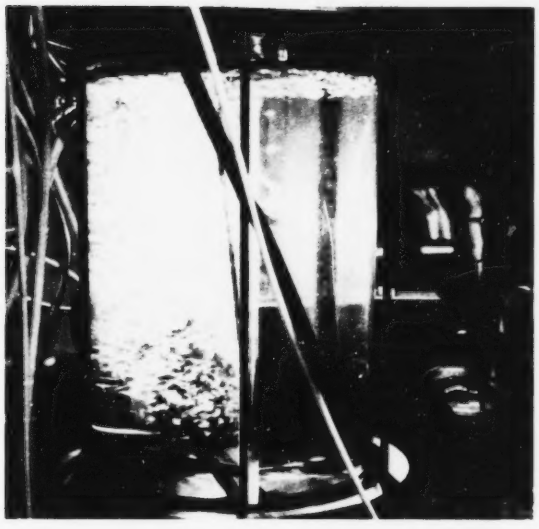

Figure 25. Perforated Bubbler with Intermediate Water Flow Rate and Propeller Off

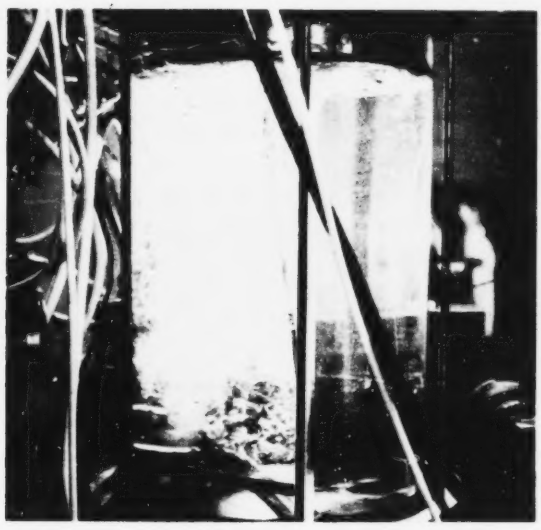

Figure 26. Perforated Bubbler with Intermediate Water Flow Rate and Propeller On

and the propeller was "off" in Figure 25 and "on" in Figure 26. Again the effect of the propeller was quite pronounced. Similar attempts were made at taking photos using the sintered bubbler and the three water flow rates, but the propeller did not seem to make as much difference in these cases.

The conditions used during the 9 special tests are summarized in Table 6 for reference, and these tests were limited to modes 1, 3, 5, and 7 of those used for the regular tests on the Mercury 650. For the special tests only, modes designated "A" were samples taken after bubbling and with the propeller off, and modes designated "B" were samples taken after bubbling and with the propeller on. In order to minimize the effect of drifting, each mode consisted of seven sampling conditions in sequence. This sequence was (1) raw exhaust; (2) bubbled exhaust with propeller off; (3) bubbled exhaust with propeller on; (4) raw exhaust; (5) same as (3); (6) same as (2); (7) same as (1). The results reported on pages D-7 through D-10 of Appendix D are concentrations on a wet basis representing averages of 3 samples for raw exhaust and 2 samples each for "A" modes and "B" modes, with sequence as indicated above. The concentrations have not been subjected

TABLE 6. CONDITIONS USED FOR SPECIAL TESTS OF THE MERCURY 650 OUTBOARD MOTOR

Special Test	Bubbler	H_2O/Exhaust Ratio	Propeller "A" Modes	Propeller "B" Modes
1	sintered	2.25	off	on
2	sintered	4.45	off	on
3	sintered	6.00	off	on
4	perforated	6.00	off	on
5	perforated	4.45	off	on
6	perforated	2.25	off	on
7	tube	2.25	off	on
8	tube	4.45	off	on
9	tube	6.00	off	on

to the Henry's Law correction, but the percentage losses to be presented in text have been corrected. Table 7, then, gives losses of HC, CO, CO_2, NO_x, and O_2 as percentages of their respective totals in raw exhaust gas. Such a table is quite difficult to interpret if examined as a whole, so the effects of several pertinent variables will be examined graphically. To make the best possible use of such data, an analysis of variance should be performed by computer, but this step has not been taken.

Figure 27 shows the apparent effect of (H_2O/exhaust) ratio on losses of hydrocarbons from the exhaust gas to the water, indicating that higher ratios are associated with greater removal of hydrocarbons. The

TABLE 7. PERCENTAGE LOSSES OF EXHAUST GAS CONSTITUENTS DURING WATER CONTACT IN SPECIAL TESTS ON MERCURY 650

Gas	Mode	Losses as Percentages of Total Amounts Present in Raw Exhaust "A" Modes of Special Test (propeller turned "off")								
		1	2	3	4	5	6	7	8	9
HC	1	27.0	31.9	44.6	39.1	30.6	22.6	22.1	29.8	35.4
	3	36.1	39.4	41.3	36.7	31.8	29.8	27.7	32.5	37.8
	5	25.1	30.7	32.1	31.4	23.1	23.1	20.6	28.5	32.2
	7	18.8	31.2	25.5	21.3	18.5	13.0	19.4	16.8	27.2
CO	1	3.88	5.81	5.18	6.65	4.34	5.64	3.34	9.79	5.28
	3	7.12	5.55	1.16	7.49	5.24	7.81	3.31	4.39	4.77
	5	0.80	2.69	5.84	4.96	2.47	3.22	3.40	4.41	6.52
	7	4.04	6.47	6.33	4.25	5.25	2.46	-0.93	3.79	6.88
CO_2	1	34.4	39.6	58.7	53.6	33.7	18.9	16.6	28.4	49.0
	3	32.2	42.0	46.8	57.6	34.5	22.4	16.6	29.3	44.7
	5	30.3	31.9	43.8	47.3	23.9	20.9	16.3	29.5	46.3
	7	32.1	28.0	45.6	39.1	24.1	15.6	15.2	25.3	39.4
NO_x	1	16.4	11.3	20.3	9.63	5.96	-0.70	7.15	9.53	12.0
	3	7.29	12.3	17.6	15.8	2.73	16.9	4.39	6.91	15.3
	5	62.3	71.0	31.1	71.1	62.2	49.6	70.8	50.6	63.3
	7	69.5	9.48	70.1	69.7	69.7	54.0	69.6	69.7	70.5
O_2	1	0.64	-0.52	0.62	-1.52	-0.86	2.64	10.6	-1.21	-2.84
	3	1.16	-8.17	-1.52	-3.64	-2.84	-1.17	3.87	0.20	-5.48
	5	0.64	0.27	0.92	0.70	-0.25	2.22	-0.73	-0.27	2.31
	7	1.66	4.35	3.23	3.06	-0.09	1.36	1.02	2.74	2.04

Table 7 continued on next page.

TABLE 7. (Cont'd). PERCENTAGE LOSSES OF EXHAUST GAS CONSTITUENTS DURING WATER CONTACT IN SPECIAL TESTS ON MERCURY 650

Gas	Mode	Losses as Percentages of Total Amounts Present in Raw Exhaust								
		"B" Modes of Special Test (propeller turned "on")								
		1	2	3	4	5	6	7	8	9
HC	1	30.7	35.6	43.5	40.7	36.0	28.6	27.6	33.2	37.0
	3	39.8	40.7	43.7	41.7	36.9	36.2	33.8	36.9	40.5
	5	28.5	36.1	37.1	32.9	27.2	26.3	25.0	32.3	33.9
	7	20.9	21.5	26.1	22.5	20.8	15.5	21.0	17.2	27.7
CO	1	5.51	1.81	1.49	4.68	5.55	4.66	3.40	4.49	6.31
	3	2.06	8.68	7.12	5.18	11.3	0.34	0.58	5.52	6.70
	5	2.82	4.21	6.98	5.41	2.80	2.94	3.49	5.63	6.67
	7	5.29	7.04	7.16	6.43	3.64	3.55	11.0	2.83	6.56
CO_2	1	43.6	45.6	54.8	54.2	46.4	28.6	26.9	41.1	52.4
	3	40.5	47.8	57.0	60.6	39.7	31.9	27.2	38.6	59.3
	5	39.4	47.1	55.8	52.9	41.0	27.5	25.8	41.6	49.4
	7	30.9	36.7	50.8	46.1	30.7	25.7	23.8	26.1	38.0
NO_x	1	20.2	13.2	17.7	16.4	3.15	9.64	9.10	13.7	12.6
	3	14.5	10.3	16.3	23.0	6.16	15.7	13.9	8.16	15.9
	5	50.3	71.5	66.0	71.2	50.5	50.0	56.7	51.3	63.4
	7	69.7	85.0	70.2	69.9	69.7	69.6	69.9	69.7	70.5
O_2	1	1.81	1.72	-2.85	1.96	2.24	-3.19	11.7	1.65	1.22
	3	-0.19	-4.52	-2.27	-3.10	-1.53	-0.35	5.00	3.16	-3.42
	5	1.60	1.83	1.04	1.18	1.24	2.88	0.44	2.27	0.14
	7	2.29	4.72	2.67	3.50	-4.22	2.04	1.99	1.91	2.93

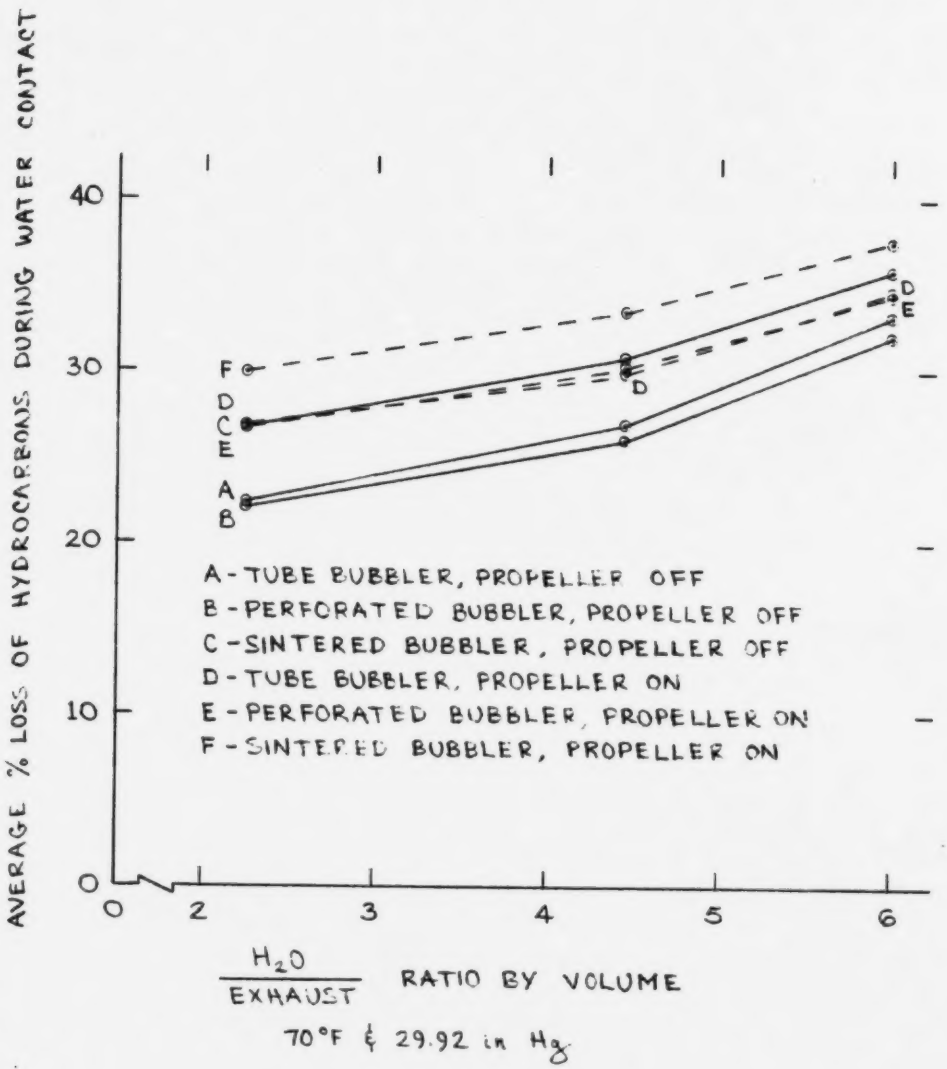

FIGURE 27. APPARENT EFFECT OF (H_2O / EXHAUST) RATIO ON LOSS OF HYDROCARBONS DURING WATER CONTACT

values plotted were obtained by averaging the 12 applicable numbers (3 bubblers x 4 modes), with the propeller off and the same with the propeller on. Since the 4 modes are being averaged together, the numbers are not particularly representative of the real situation, so it could be said that the engine was being used as a fairly repeatable gas generator for the special tests. In naming Figure 27 and several later graphs, the term "apparent" effect is used because it is simply not certain that the change in the dependent variable shown is due (either entirely or in part) to change in the independent variable. Within reasonable limits, for instance, the change in hydrocarbon removal observed could be due to water turbulence rather than flowrate, but the (H_2O/exhaust) ratio can be assigned a number much more readily. These same general comments are equally applicable to Figures 28 and 29, which show the apparent effect of water flowrate on losses of CO_2 (Figure 28), and O_2 and CO (Figure 29). A comparable figure was not constructed for NO_x due to the extremely large variation in NO_x between modes, which would have created misleading averages.

Figure 30 shows the apparent effect of raw exhaust concentrations on losses of HC, CO_2, and NO_x in the bubbling system. The effect shown for CO_2 is probably due simply to concentration, but those shown for HC and NO_x are probably due more to changes in the composition of the classes of compounds. Hydrocarbons, for instance, probably are composed of larger fractions of unburned fuel and smaller fractions of combustion products as their overall concentrations increase, which could lead to lower fractional losses as concentrations increase. Oxides of nitrogen are predominantly NO at higher concentrations, but can contain substantial fractions of NO_2 at low overall concentrations. The NO is not very soluble, but NO_2 dissociates in water, and thus is removed readily by water, and it is this effect which probably leads to the relationship for NO_x shown in Figure 30.

It is quite clear that much additional analysis could be performed on these data, and that only a modest start has been made, but more extensive analysis is outside the scope of this project at least for the present. A good place to begin from here is probably the analysis of variance suggested earlier. No serious attempt has been made to evaluate changes in composition of the water going through the contact system by direct measurement. The preliminary studies on this subject which have been conducted indicate that most process-type water analysis methods do not have the sensitivity required for good quantitative results, and that more sensitive techniques are very laborious and/or expensive.

C. Results of Emissions Tests on the Chrysler 35 hp Outboard Motor Using a 3rd Order Power Curve

The test results on the Chrysler 35 hp engine which were presented in Section IV. A were generated while the engine was running on a 2.5 order power curve, which is considered most typical for this engine in

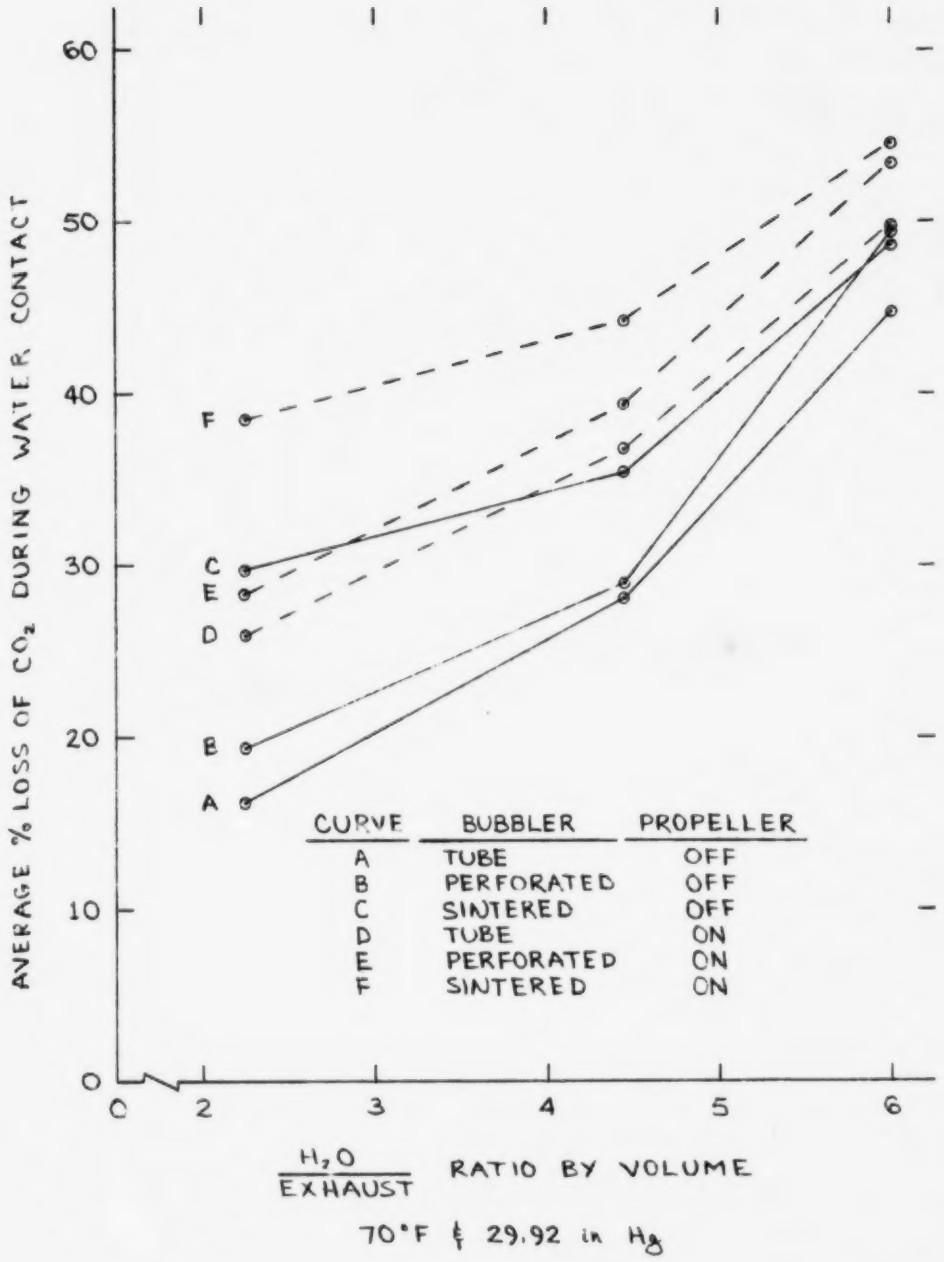

FIGURE 28. APPARENT EFFECT OF (H_2O/EXHAUST) RATIO ON LOSS OF CO_2 DURING WATER CONTACT

CURVE	BUBBLER	PROPELLER
A	TUBE	OFF
B	PERFORATED	OFF
C	SINTERED	OFF
D	TUBE	ON
E	PERFORATED	ON
F	SINTERED	ON

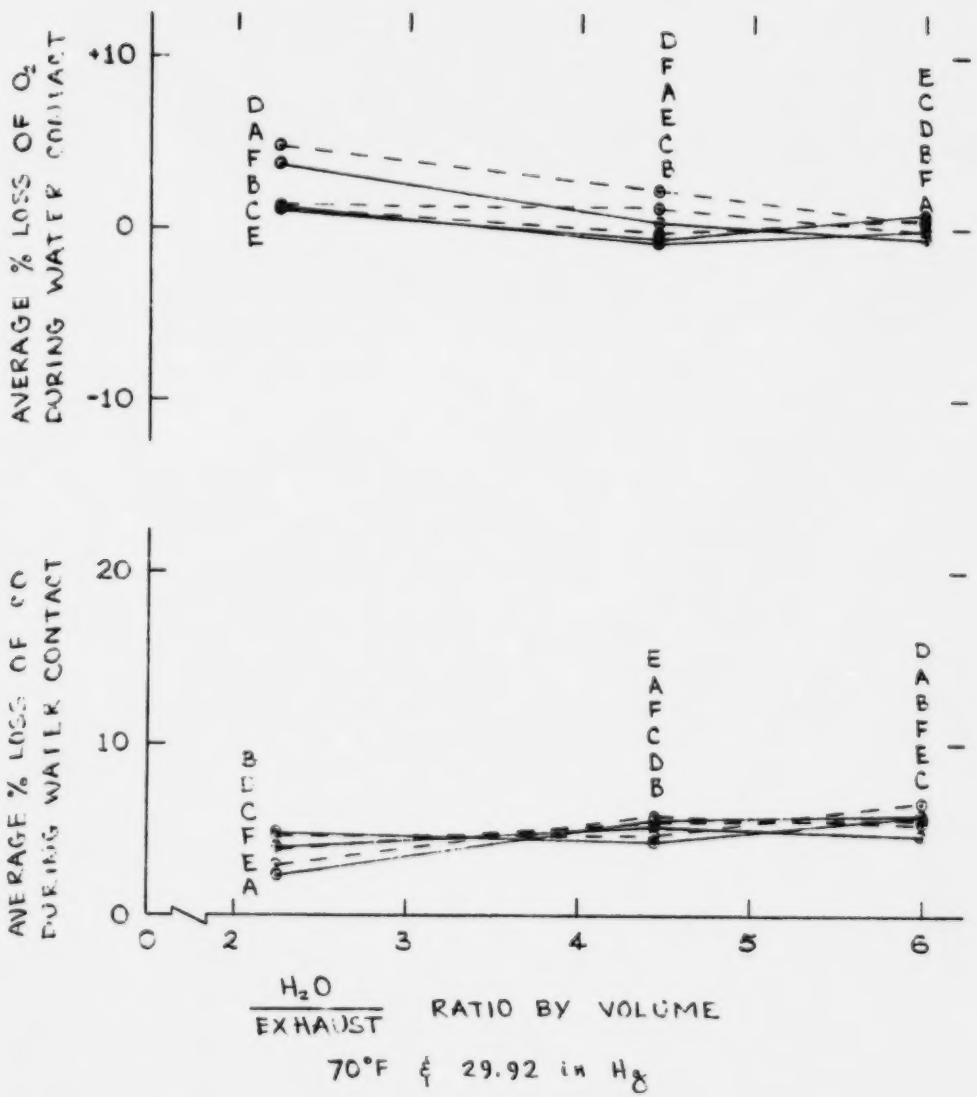

FIGURE 29. APPARENT EFFECT OF (H_2O/EXHAUST) RATIO ON LOSSES OF OXYGEN AND CO DURING WATER CONTACT

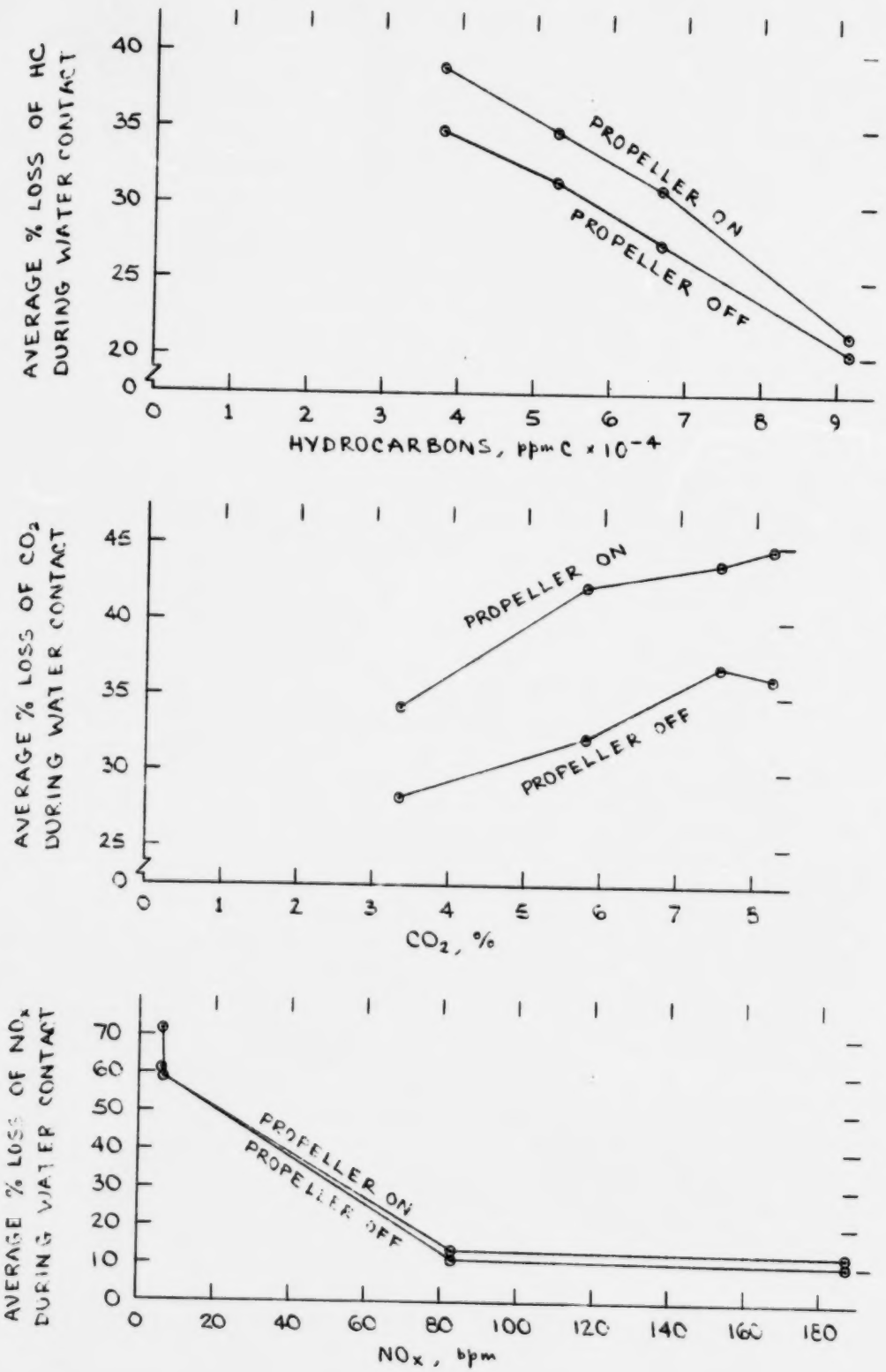

FIGURE 30. APPARENT EFFECT OF CONCENTRATION ON LOSSES OF HC, CO_2, AND NO, DURING WATER CONTACT

pleasure boat service. In addition to the five runs using the 2.5 order power curve, however, two runs were made using a 3.0 order curve, which reduced the power output somewhat in Modes 2, 3, 4, and 5. Mode 1 (maximum power) would have remained the same, so it was not run; and Mode 6 (idle) would likewise not have changed, so it was not run. The crankshaft and propeller shaft power points were given in Tables 1 and 2, so they will not be repeated here.

Table 8 gives mass emissions data on a 3.0 order power curve analogous to those found in Table 3 for the four engines operated on power curves considered "normal". The data in Table 8 have already been plotted (curves labeled x = 3 for the Chrysler in Figures 15 through 18), and they compare quite closely with those generated using higher loads. Differences in NO_x and CO_2 were so small as to be almost negligible, but CO was higher and hydrocarbons were lower at the higher speeds when power output (and consequently mass flow) were reduced.

TABLE 8. TOTAL MASS EMISSIONS AND MASS EMISSIONS RETAINED IN WATER PHASE (EXPERIMENTALLY) FOR A CHRYSLER 35 HP OUTBOARD MOTOR OPERATED ON A 3.0 ORDER POWER CURVE

	Raw Mass Emission Rate, g/hr			
Gas	Mode 2	Mode 3	Mode 4	Mode 5
HC	1640	1340	1080	880
CO	6340	4350	2580	1140
CO_2	9720	6580	3870	1840
NO_x	6.32	3.60	1.44	0.64
O_2	3140	2510	2240.	1700
H_2O	8430	5770	3230.	1580

	Loss in Water (Experimental), g/hr			
Gas	Mode 2	Mode 3	Mode 4	Mode 5
HC	613	496	426	328
CO	299	239	205	74.5
CO_2	3910	2690	1640	796
NO_x	2.78	1.99	0.94	0.54
O_2	- 21.5	- 148	32.0	38.6
H_2O	6740	4570	2490	1180

The trend reversed itself at lower speeds for hydrocarbons, but remained the same for CO. If emissions were to be studied as a function of load at fixed speeds, a wider range of loads would be necessary to get meaningful variation. For the purposes of the present study, however, the limited amount of work performed with the one engine indicates that mass emissions probably do not vary strongly over the range of power outputs to be expected at one crankshaft speed.

V. ESTIMATION OF EMISSION FACTORS AND NATIONAL IMPACT

The quantities essential to determining emission factors for outboards are mass-based emissions data and information on duty cycles (fractions of operating time spent in various speed bands). Estimation of national impact further requires data on annual usage, number of motors in service, and composition of the population of motors according to size. It is also relatively simple to calculate emission factors on a fuel basis, but use of these factors in determining impact requires the assumption of national fuel usage, not a readily documented quantity. It any case, fuel-based factors will be calculated and the corresponding impact analysis will be attempted, based on available information

As discussed in the section on results, outboards actually discharge their exhaust underwater, so measurements were taken both before and after the exhaust was bubbled through water in a simulator in an attempt to take the water scrubbing process into account. In this context, outboard "atmospheric" emissions means the portion of total outboard emissions which made its way through the bubbling process without being retained in the water. No assertion is made that the laboratory process takes into account the time factor which exists in the real situation, that is, the subject work has involved no attempt to determine the ultimate fate of exhaust products. This assumption of a static situation is undesirable, but nevertheless necessary in lieu of experimental data.

A. Development of Emission Factors

The emissions data on which the factors will be based are given in section IV. A. It would be more desirable, of course, to be able to base emission factors on a greater number of engines, but additional data are simply not available. The other major items of information required are duty cycles for outboards, expressed in fractions of time spent in each attainable speed band. Data developed by Outboard Marine Corporation in a rather extensive outboard motor usage survey[3] are shown in Table 9, representing about 200 hours of data acquisition. The "100 hp and up" engine category included three engines, the 50-55 hp category included three engines, the 40 hp data are from a single engine, and the 9.5 hp data represent four engines. To make the best use of these data, they have been regrouped on larger rpm intervals corresponding to the engine speeds used for testing, and are presented as Table 10. The OMC data developed on the 9.5 hp engines was used to determine mode weights for both the 4 hp and 9.5 hp test engines, an average of OMC data developed for 50-55 hp engines and 9.5 hp engines was used to determine mode weights for the Chrysler 35 hp engine, and the OMC data on 50-55 hp engines was used alone to determine mode weights for the Mercury 65

TABLE 9. OMC OUTBOARD MOTOR OPERATING TIME DATA

Rpm Range	Percent of Operating Time in rpm Range by Engine Size			
	100 hp & up	50-55 hp	40 hp	9.5 hp
500-1000	30	7	3	8
1000-1500	15	17	13	12
1500-2000	5	10	12	10
2000-2500	3	7	7	10
2500-3000	3	4	3	6
3000-3500	8	8	13	13
3500-4000	12	13	13	12
4000-4500	18	23	19	16
4500-5000	4	5	12	11
5000-5500	2	4	5	2
5500-6000	-	2	-	-

TABLE 10. TIME-BASED WEIGHTING FACTORS FOR TEST MODES

Mode	Fraction of Operating Time in Modes by Engine (W_i)			
	OMC 4 hp	OMC 9.5 hp	Chrysler 35 hp	Mercury 65 hp
1	0.21	0.21	0.12	0.06
2	0.20	0.20	0.32	0.05
3	0.19	0.19	0.15	0.36
4	0.20	0.20	0.18	0.12
5	0.10	0.10	0.12	0.17
6	0.10	0.10	0.11	0.12
7	-	-	-	0.12

hp engine. To make the arithmetic of the emission factor calculations more compact, a few terms should be defined.

let: W_i = individual time-based mode weighting factors;
M_i = individual mode mass emission rates (g/hr);
hp_i = crankshaft horsepower developed in individual modes;
n = number of modes (6 or 7)

Using these terms to compute emission factors, we have

$$\text{composite (cycle) mass emissions (g/hr)} = \sum_{i=1}^{n} W_i M_i \ ;$$

$$\text{average crankshaft power developed during cycle (hp)} = \sum_{i=1}^{n} W_i hp_i \ ;$$

$$\text{composite brake specific emissions } \left(\frac{g}{hp\ hr}\right) = \frac{\sum_{i=1}^{n} W_i M_i}{\sum_{i=1}^{n} W_i hp_i};$$

$$\text{composite load factor} = \frac{\text{average power used (hp)}}{\text{maximum power available (hp)}}$$

$$= \frac{\sum_{i=1}^{n} W_i hp_i}{\text{Maximum rated power (hp)}}$$

If it were desirable to compute fuel specific emissions for some reason, assuming that

F_i = individual mode fuel rate (gal/hr),

then

$$\text{composite fuel specific emissions (g/gal fuel)} = \frac{\sum_{i=1}^{n} W_i M_i}{\sum_{i=1}^{n} W_i F_i}$$

and

$$\text{composite brake specific fuel consumption (gal fuel/hp hr)} = \frac{\sum_{i=1}^{n} W_i F_i}{\sum_{i=1}^{n} W_i hp_i}$$

Individual mode brake specific emissions and fuel specific emissions would be given by M_i/hp_i and M_i/F_i, respectively.

Table 11 shows the procedure for calculation of composite (cycle average) power outputs and load factors, and Table 12 gives the procedure for calculation of composite fuel consumption and composite brake specific fuel consumption. These calculated quantities can be used in conjunction with the sums of the weighted mass emissions for each engine to determine the composite brake specific and fuel specific

TABLE 11. COMPOSITE POWER OUTPUT AND LOAD FACTOR CALCULATIONS

Mode	Weighted Crankshaft Power Output by Engine ($W_i hp_i$) OMC 4 hp	OMC 9.5 hp	Chrysler 35 hp	Mercury 65 hp
1	0.84	2.00	4.20	3.90
2	0.56	1.42	6.40	2.66
3	0.23	0.66	1.47	12.13
4	0.07	0.25	0.63	1.79
5	0.01	0.02	0.07	1.02
6	0.00	0.00	0.00	0.13
7	-	-	-	0.00
Composite Power Output (hp) $= \sum_{i=1}^{n} W_i hp_i =$	1.71	4.34	12.77	21.62
Composite Load Factor $= \frac{\sum_{i=1}^{n} W_i hp_i}{\text{maximum power}} =$	0.427	0.457	0.365	0.333

emissions. The steps leading to these specific emissions results are outlined in Table 13, and the composite specific emissions listed are those which will be used in estimating national impact. It has been noted previously that the regular tests on the four outboards were performed using a variety of combinations of water:exhaust gas ratio and induced turbulence. In order to avoid the confusion this variation might cause, the combination will be "standardized" for the purposes of the emission factor calculations as: (1) perforated bubbler; (2) water:exhaust gas ratio 4.45:1; and (3) propeller "on". This combination was used for tests on the Chrysler 35 hp and Johnson 9.5 hp motors, but not for the other two, so consideration has been given to modification of the measured losses in the water phase for the Johnson 4 hp and Mercury 65 hp engines. This consideration has lead to the arbitrary decision that the measured CO_2 and HC losses for the Johnson 4 hp motor should be multiplied by 1.18

TABLE 12. COMPOSITE FUEL CONSUMPTION AND BSFC CALCULATIONS

Mode	Weighted Fuel Consumption by Engine (W_iF_i) gal/hr			
	OMC 4 hp	OMC 9.5 hp	Chrysler 35 hp	Mercury 65 hp
1	0.139	0.277	0.503	0.451
2	0.090	0.239	0.890	0.302
3	0.059	0.188	0.300	1.444
4	0.040	0.128	0.224	0.332
5	0.016	0.033	0.080	0.331
6	0.016	0.028	0.081	0.206
7	-	-	-	0.148
Composite Fuel Consumption (gal/hr) = $\sum_{i=1}^{n} W_iF_i$ =	0.360	0.893	2.077	3.215
Composite BSFC (gal/hp hr) = $\frac{\sum_{i=1}^{n} W_iF_i}{\sum_{i=1}^{n} W_ihp_i}$ =	0.211	0.206	0.163	0.149

and those for the Mercury 65 hp motor by 1.05. The decision is based on differences in CO_2 losses for the four engines, and will be assumed to apply only to CO_2 and HC since for NO_x and CO losses in water, no strong dependence on turbulence has been established.

It is conceded that the choices made in determination of factors have been arbitrary, but consider the following rationale:

(1) It has been established in the special tests of the Mercury 650 that losses of condensable and/or soluble exhaust constituents in the water phase exhibit a positive dependence on some combination of water:exhaust ratio and turbulence.

(2) It has been established that losses of exhaust products in the water phase can be significantly greater than those assumed

for calculation purposes (if turbulence, etc., are varied).

(3) The real situation very probably entails a combined index of water:exhaust ratio and turbulence at least as high as that assumed for calculation purposes.

(4) Other variables which may have some effect on removal of exhaust constituents during water scrubbing, such as water temperature, bubble residence time (as a function of depth), and water pH, were documented in the subject studies as being within reasonable ranges which might be encountered in the field.

Thus the choices made constitute a "middle of the road" approach which is justified by the overall limits of the study, and indeed some choices had to be made before any results could be determined at all. No

TABLE 13. INDIVIDUAL AIR AND WATER BRAKE SPECIFIC AND FUEL SPECIFIC EMISSION FACTORS FOR FOUR OUTBOARD MOTORS

		Composite Factors, Atmospheric			Composite Factor, Water Phase		
Engine	Constituent	Mass, g/hr	Brake Specific, g/hp hr	Fuel Specific, g/gal fuel	Mass, g/hr	Brake Specific, g/hp hr	Fuel Specific, g/gal fuel
OMC 4 hp	*HC	195.	114.	542.	102.	59.9	284.
	CO	413.	241.	1150.	53.7	31.4	149.
	*CO_2	871.	509.	2420.	574.	336.	1590.
	NO_x	1.24	0.72	3.4	0.34	0.20	0.95
OMC 9.5 hp	HC	393.	90.6	440.	302.	69.6	338.
	CO	1280.	295.	1430.	68.2	15.7	76.4
	CO_2	2140.	493.	2400.	1460.	336.	1630.
	NO_x	2.34	0.53	2.6	0.26	0.060	0.29
Chrysler 35 hp	HC	991.	77.6	477.	627.	49.1	302.
	CO	4010.	314.	1930.	208.	16.3	100.
	CO_2	4240.	332.	2040.	2640.	207.	1270.
	NO_x	2.97	0.23	1.4	1.37	0.11	0.66
Merc. 65 hp	**HC	1780.	82.5	555.	889.	41.1	277.
	CO	4090.	189.	1270.	139.	6.45	43.4
	**CO_2	7740.	358.	2410.	5680.	262.	1770.
	NO_x	14.2	0.65	4.4	2.44	0.11	0.76

*calculated loss in water multiplied by 1.18 to achieve these results
**calculated loss in water multiplied by 1.05 to achieve these results

assertion is made that the chosen results actually represent the real situation, but they do constitute a reasonable estimate.

The most notable feature of the data given in Table 13 is the extremely good consistency of the brake specific and fuel specific emissions from engine to engine, considering the variations in size and general physical configuration. The consistency is even better if variations in the effects of water scrubbing are removed by combining the atmospheric and water factors to yield the total emission factors, as has been done in Table 14. The only major variations in these data occur in NO_x (which was present in very small amounts and exhibited large concentration variability), and in CO-CO_2 balance for the Chrysler (which was weighted much more heavily toward CO production than was the case for the other 3 engines).

TABLE 14. TOTAL EMISSION FACTORS FOR FOUR OUTBOARD MOTORS (Combined Atmospheric and Water Phase Factors)

Engine	Constituent	Mass, g/hr	Brake Specific, g/hp hr	Fuel Specific, g/gal fuel
OMC 4 hp	HC	297.	174.	825.
	CO	467.	273.	1300.
	CO_2	1440.	845.	4010.
	NO_x	1.58	0.92	4.39
OMC 9.5 hp	HC	695.	160.	778.
	CO	1350.	311.	1510.
	CO_2	3600.	829.	4030.
	NO_x	2.60	0.60	2.91
Chrysler 35 hp	HC	1620.	127.	779.
	CO	4220.	330.	2030.
	CO_2	6880.	539.	3310.
	NO_x	4.34	0.34	2.09
Mercury 65 hp	HC	2670.	123.	830.
	CO	4230.	196.	1320.
	CO_2	13400.	620.	4170.
	NO_x	16.6	0.77	5.18

These emission factors do not include crankcase drainage, which is a mixture of fuel-based (liquid and gaseous) hydrocarbons and air emitted from the crankcases of some outboard motors. For the test engines in particular, two (Mercury 65 hp and OMC 9.5 hp) had drain recirculation, one did not (Chrysler 35 hp), and the last (OMC 4 hp) could not be verified one way or the other. Exhaust emissions from the

engines with recirculation correctly characterize their total emissions, whereas crankcase drainage would be considered separately for engines without recirculation. There are several possible effects on total emissions due to un-recirculated crankcase drainage.

(1) Fuel which drains from the crankcase may be incorrectly included as part of the total fuel used to calculate mass emissions, making the calculated mass emissions higher than actual.

(2) It might be possible in some engines to measure exhaust emissions at a point far enough downstream such that the inducted mixture and the drainage would have already mixed. This type of sampling would give accurate results if all the drainage had vaporized, but would probably not be accurate if part of the drainage were still liquid.

(3) One technically correct way of dealing with the drainage would be to measure it on a mass basis (including condensable hydrocarbon vapors), and subtract it from the externally-measured fuel consumption before calculating mass emissions. The drainage measured could then simply be added to the total hydrocarbon emissions without affecting the other constituents.

The possible ramifications of the crankcase drainage situation simply had not been considered before the subject tests were run, so the results given here will be for raw exhaust not mixed with drainage, and the fuel rates used for mass emissions will be the externally-measured fuel rates. Based on the results of the companion study on crankcase drainage currently being conducted, the probable errors inherent in the less-than-rigorous procedures used here are a fraction of a percent for the Chrysler 35 hp engine and a few percent (perhaps 2 or 3 percent) for the OMC 4 hp engine (if it does emit drainage at all). These percentages are for cycle composite emissions, with the larger probable errors occurring at low speeds and the smaller ones at high speeds.

B. Estimation of National Impact

The primary source of outboard motor population and utilization data at the present time is the Boating Industry Associations (BIA)[4]. Other industry sources[5, 6] help to fill in the short-term historical picture, but most of the statistics given are oriented toward industry economics rather than population and usage. A summary of the major usable population and sales statistics[4, 5] is given in Table 15, including an assumption[7] of average motor horsepower for the years before 1949. The report just referenced contains some very useful calculations on

TABLE 15. SUMMARY OF OUTBOARD MOTOR POPULATION AND SALES DATA

Year(s)	Sales x 10^{-3}	Percentage of Sales by hp Class 0-6.9	7.0-19.9	20.0-44.9	20.0 & up	45.0 & up	Avg. hp Sold	Outboard Motors in Use x 10^{-3}
1919-1930	357.4							-
1931-1941	775	-1942-1945 No Production						-
1946	398						5.0	-
1947	584						(Assumed)	-
1948	499							-
1949	329						6.4	2643
1950	367						6.9	2811
1951	284						8.9	3010
1952	337						8.4	3219
1953	463						9.0	3419
1954	479						10.3	3740
1955	515	36	48		16		12.9	4210
1956	642	27	47		26		14.2	4700
1957	550	22	42		36		16.3	5040
1958	504	17	40		43		20.7	5385
1959	540	17	34		49		23.7	5650
1960	468	16	27		57		27.4	5800
1961	343	17	25	39		19	29.9	6100
1962	360	17	25	38		20	30.3	6244
1963	362	19	24	35		22	30.5	6390
1964	390	21	25	30		24	30.3	6564
1965	393	19	38	19		24	28.2	6645
1966	440	25	30	21		24	29.9	6784
1967	444	28	23	22		27	30.1	6904
1968	500	29	21	21		29	31.5	6988
1969	510	28	19	19		34	33.1	7101
1970	430	27	22	21		30	31.0	7215
1971	495	22	19	19		40	35.6	7300

an outboard motor population model, and the one which seems to fit the available data fairly well is

$$\text{fraction of motors of age "A" still in use} = e^{-kA^2} = F_j ,$$

where $k = 2.83 \times 10^{-3}\ \text{yr}^{-2}$ and A = motor age in years. Using this expression and designating individual motor ages as A_j, the current motor population is

$$\text{sum of motors still in use} = \sum_{j=o}^{j=n} N_j e^{-kA_j^2}$$

where n = number of years backward over which the analysis extends and N_j = number of motors sold in each individual year. The report[7] verified that the above model gave reasonable approximations of the actual 1960 and 1965 motor populations when applied over the time spans prior to those years. In addition, the 1949 motor population was calculated using the model for additional verification and the prediction was within 5% of the value for 1949 listed in Table 15.

The application of the population model which is of most interest in this study is in calculation of the average power of engines in the field. The calculations leading to the desired result are summarized in Table 16 (where hp_j = average power of motors sold during each individual year), and the average power computed is

$$\text{average power} = \frac{\sum_{j=1}^{n} S_j \, hp_j}{\sum_{j=1}^{n} S_j} = 24.6 \text{ hp}$$

If all engines produced prior to 1946 are neglected, the average power is slightly higher but still rounds to 24.6 hp. Just to make sure the above estimate was reasonable, a much less accurate approximation was calculated by assuming that the 7.3 million newest motors were those still in use at the end of 1971. This approximation yielded an average power of 27.0 hp, indicating not only that the more soundly-based estimate is reasonable, but also that the older motors play only a minimum role in determining average power of engines in the field.

Another important use of the data in Table 15 is in formulating an estimate of the percentage of motors which fall into each of the four (more modern) power categories. The process here will be to calculate the surviving population in each power category by weighting each year's total surviving population (S_j) by fraction produced in each power category. From 1960 back to 1955, it will be assumed that the "20 hp & up" category is composed 75% of "20.0-44.9 hp" motors and 25% of "45 hp & up" motors. Prior to 1955, the "20 hp & up" category will be extrapolated linearly to zero over a period of four years, assuming an average of 25 hp. Again prior to 1955, it will be assumed that engines in the "0-6.9 hp" category averaged 5 hp, and that those in the "7.0-19.9 hp" category averaged 15 hp. These assumptions permit the calculations to be extended back to the earliest available data, as shown in Table 17 along with the results of the calculations.

Having arrived at the population breakdown shown at the bottom of Table 17, most of the information required for the impact calculations has been developed, with one of the exceptions being average annual

TABLE 16. SUMMARY OF CALCULATIONS LEADING TO AVERAGE POWER OF OUTBOARD MOTORS IN USE AT THE END OF 1971

Year(s)	Age = A_j, yr.	$F_j = e^{-kA_j^2}$	Sales = N_j ($\times 10^{-3}$)	Surviving Motors = $S_j = F_j N_j (\times 10^{-3})$	Power of Surviving Motors = $S_j hp_j (\times 10^{-3})$, hp
1919-1930	*46.5	*0.00222	357.4	0.793	3.97
1931-1941	*35	*0.0312	775	24.2	121.
1946	25	0.171	398	68.1	340.
1947	24	0.196	584	114.	570.
1948	23	0.224	499	112.	560.
1949	22	0.254	329	83.6	535.
1950	21	0.287	367	105.	724.
1951	20	0.322	284	91.4	813.
1952	19	0.360	337	121.	1020.
1953	18	0.400	463	185.	1660.
1954	17	0.441	479	211.	2170.
1955	16	0.485	515	250. — 18.5%ile	3220.
1956	15	0.529	642	340.	4830.
1957	14	0.574	550	316.	5150.
1958	13	0.620	504	312.	6460.
1959	12	0.665	540	359.	8510.
1960	11	0.710	468	332.	9100.
1961	10	0.754	343	259.	7740.
1962	9	0.795	360	286.	8670.
1963	8	0.834	362	302. — 48.7%ile	9210
1964	7	0.871	390	340.	10300.
1965	6	0.903	393	355.	10000.
1966	5	0.932	440	410. — 62.3%ile	12300.
1967	4	0.956	444	424.	12800.
1968	3	0.975	500	488. — 73.8%ile	15400.
1969	2	0.989	510	504.	16700.
1970	1	0.997	430	429. — 87.3%ile	13300.
1971	0	1.000	495	495.	17600.
			$\sum_j$ =	7317.	179700.
Neglecting 1919-1941			$\sum_j$ =	7292.	179600.

*Median value for the range of years assumed.

TABLE 17. SUMMARY OF CALCULATIONS LEADING TO FRACTIONS OF OUTBOARD MOTORS IN SERVICE IN FOUR POWER CATEGORIES

	Surviving Motors in Horsepower Category x10^{-3}			
Year(s)	0-6.9	7.0-19.9	20.0-44.9	45 & up
1919-1930	0.793			
1931-1941	24.2			
1946	68.1			
1947	114.			
1948	112.			
1949	71.9	11.7		
1950	85.0	20.0		
1951	55.8	35.6		
1952	84.7	31.5	4.84	
1953	126.	44.4	14.8	
1954	124.	61.2	25.3	
1955	90.0	120.	30.0	10.0
1956	91.8	160.	66.3	22.1
1957	69.5	133.	85.3	28.4
1958	53.0	125.	101.	33.5
1959	61.0	122.	132.	44.0
1960	53.1	89.6	142.	47.3
1961	44.0	64.8	101.	49.2
1962	48.6	71.5	109.	57.2
1963	57.4	72.5	106.	66.4
1964	71.4	85.0	102.	81.6
1965	67.4	135.	67.4	85.2
1966	102.	123.	86.1	98.4
1967	119.	97.5	93.3	114.
1968	142.	102.	102.	142.
1969	141.	95.8	95.8	171.
1970	116.	94.4	90.1	129.
1971	109.	94.0	94.0	198.
Total	2303.	1990.	1648.	1377.
Fraction of Total	0.315	0.272	0.225	0.188

usage. No credible usage data are currently available, so estimates of 50 hours per year for an outboard motor[8] and 75 hours per year for an outboard boat[13] will be considered. Assuming that there were 7.3 million outboard motors in use at the end of 1971, the above estimate of motor usage yields 365 million motor hours per year. The latter estimate of 75 boat hours per year combined with an industry figure for outboard boats in use (5.315 million)[4] yields 399 million boat hours per year. Assuming that an outboard boat always has a motor pushing it (sometimes 2 motors), the boat usage method results in a higher motor usage estimate than the motor usage method does. Since so many approximations and assumptions are necessary for this report, it is deemed appropriate to choose the estimate which will result in the more conservative impact estimate for outboards, namely that each motor is used 50 hours per year.

To be really rigorous in calculating impact, average power output for engines in each of the four power categories is needed. These values could be multiplied by the population fractions at the bottom of Table 17 to determine a "power-weighted" population breakdown, but they cannot be extracted from the available data. The only alternative is to assume a value for average horsepower in each power category, and check the resulting average power output for all motors against the known average value of 24.6 hp. Assuming values of 5 hp, 15 hp, 35 hp, and 65 hp for the four categories, the resulting average power output is 25.8 hp (close enough to the known value) and the weighting factors for the categories become (in order of increasing power) 0.0612, 0.158, 0.306, and 0.475. These factors are "full power" weighting factors, so to derive a representation of the breakdown of power generated in the field, they must be multiplied by their respective load factors given at the bottom of Table 11. This process yields the factors 0.0261, 0.0722, 0.112, and 0.158 (designated W_k = (hp generated by engines in category/(total hp available)) for the power categories in order of increasing power, and their sum (0.368) is the overall composite load factor for the entire motor population.

The power-based impact calculations now take the form

$$\frac{\text{ton}}{\text{yr}} = (\text{engine population})\,(\text{avg. hp})\,(\text{usage, } \frac{\text{hr}}{\text{yr}})\,\left(\frac{1\ \text{ton}}{9.027\text{x}10^5\text{g}}\right)\left(\sum_{k=1}^{4} W_k B_k\right)$$

where the B_k are brake specific emission factors for the four engines in g/hp hr.

Filling in the constants, this formula becomes

$$\frac{\text{ton}}{\text{yr}} = 9.90\text{x}10^3 \left(\sum_{k=1}^{4} W_k B_k\right).$$

Note that the "full power" weighting factors are used only to determine how much weight is given to brake specific emission factors for each engine, not to calculate impact directly, which makes calculated impact relatively insensitive to the accuracy of the assumed averages.

To calculate impact on a fuel basis, it is first necessary to compute the fractions of total fuel used by engines in each category. These fractions can be calculated by

$$Q_k = (\text{fraction of fuel})_k = \frac{(\text{fraction hp generated})_k\,(BSFC)_k}{\sum_{k=1}^{4} (\text{fraction hp generated})_k\,(BSFC)_k}$$

$$= \frac{W_k BSFC_k / \sum_{k=1}^{4} W_k}{\sum_{k=1}^{4} (W_k BSFC_k / \sum_{k=1}^{4} W_k)}$$

where $BSFC_k$ = brake specific fuel consumption (gal/hp hr) for each category. The fuel-based impact calculations now assume the form

$$\frac{\text{ton}}{\text{yr}} = (\text{total fuel usage, gal/yr})\left(\frac{1\text{ ton}}{9.072\text{x}10^5\text{g}}\right)\left(\sum_{k=1}^{4} Q_k F_k\right)$$

where the F_k are the fuel specific emission factors for the four engines in g/gal. The four values for Q_k (for the categories in order of increasing power) are 0.0888, 0.239, 0.293, and 0.378. The latest widely-quoted figure for fuel consumption by pleasure boats is 1.1 billion ($1.1\text{x}10^9$) gallons for the year 1971[5]. This figure is intended to include fuel used by inboard/outdrive units (255,000) and gasoline-powered inboards (730,000 total inboards, no separate estimates for diesel and gasoline)[15]. If it is assumed that the total inboards included the inboard/outdrives, and that 75% of inboards used gasoline rather than diesel fuel, it could be estimated that about 550,000 gasoline inboards were in use at the end of 1971. If it is further assumed: that the inboard engines averaged 100 hp; that they were used 75 hours per year; that their average fuel consumption was 0.08 gal/hp hr; and that their average composite load factor was 0.333; then it can be estimated that gasoline inboards used about 0.11 billion gallons of fuel in 1971. This amount is 10% of the total gasoline figure given above, making the estimated total for outboards $0.99\text{x}10^9$ gallons. Although this estimate has been derived from the only industry figure available, it is considered to be unrealistically high because the industry fuel consumption figure is likewise considered

high. Calculations will be carried out on both annual usage and fuel bases for comparison, but impact calculated on the fuel basis will not be assumed reliable.

Using the equations and statistics given above, the national impact of outboard motor emissions for 1971 has been computed on both brake specific and fuel specific bases. The impact data are given in Table 18 for total emissions as well as those calculated to end up in the atmosphere and in the water using assumptions stated earlier. As noted in the title of Table 18, the impact numbers are for 2-stroke water-cooled engines only. All inboard, inboard/outdrive, air-cooled outboard, and 4-stroke outboard motors are excluded from the impact estimate, the latter two categories being assumed to have negligible impact and the former two being omitted because they are outside the intended scope of this project.

TABLE 18. NATIONAL IMPACT ESTIMATES FOR TWO-STROKE WATER-COOLED OUTBOARD MOTOR EMISSIONS, 1971

	Total Estimated Emissions, 10^6 tons per year	
Contaminant	Brake Specific Basis	Fuel Specific Basis
HC	0.494	0.826
CO	0.965	1.62
CO_2	2.38	3.98
NO_x as NO_2	0.0022	0.00377
SO_x as SO_2	0.00106	0.00188

	*Estimated Atmospheric Emissions, 10^6 tons per year	
Contaminant	Brake Specific Basis	Fuel Specific Basis
HC	0.310	0.520
CO	0.917	1.54
CO_2	1.41	2.37
NO_x as NO_2	0.0018	0.0031
SO_x as SO_2	0.00100	0.00178

	*Estimated Water Phase Emissions, 10^6 tons per year	
Contaminant	Brake Specific Basis	Fuel Specific Basis
HC	0.184	0.308
CO	0.0475	0.0796
CO_2	0.966	1.62
NO_x as NO_2	0.00039	0.00066
SO_x as SO_2	0.000058	0.000102

*subject to qualifications given earlier.

In the case of outboard motors, evaporative losses of fuel have not been included in the impact estimates for several reasons. Spillage and evaporation losses during fueling and fuel/oil mixing may be significant, but no data on these losses are available. Evaporation from the carburetor during running is probably of less significance, but in any case no data are available on this point either. It stands to reason that "hot soak" losses such as those from automobile probably do not occur, since outboard carburetors do not sit directly on top of the engines and are not subjected to strong heat input following engine shutdown.

Evaporation from the fuel tank can occur if the tank vent does not incorporate a one-way valve (preventing flow out of the tank) and if the vent is left open. The fraction of tanks fulfilling these requirements for evaporation is not known, however, so tank losses cannot be estimated. In summary, it is highly probable that some evaporation losses occur, but information necessary to a quantitative assessment of these losses is not available.

The estimates of sulfur oxides (SO_x) impact are based on a fuel sulfur content of 0.043% by weight[14] and the assumption that all the sulfur which is oxidized at all is oxidized fully to SO_2. It is also assumed that the fraction of sulfur being oxidized to SO_2 is the same as the fraction of fuel being burned, a necessary assumption for 2-stroke engines, and that the remainder is emitted as elemental sulfur (and not included in the impact estimate).

The determination of which set of impact numbers (brake specific or fuel specific) is more accurate hinges on the accuracy of the major assumptions made about yearly usage and fuel consumption. The problem with fuel consumption data is that the data-gathering process is prohibitively complicated, so it must be assumed that published numbers are no more than educated guesses. The estimate used for annual usage is probably a guess also, but it seems reasonable (it can be dealt with in terms of personal experience, whereas national fuel consumption cannot) and it could be checked by a statistical survey much more easily than fuel consumption could be. At this point, then, the emissions impact calculated on a brake specific basis is considered more reliable, and will be used to compare to EPA Inventory Data.

Another note on the applicability of the impact figures given in Table 18 concerns the inclusion of older motors in a population characterized by tests on new motors. If the design of outboards had been highly evolutionary (at least in those sub-systems which might influence emissions drastically), the age disparity would be a subject of concern. Such drastic changes have not occurred, however, so it is doubtful that emissions from older engines are greatly different than those from newer engines.

It should also be noted that this study forms no basis for determining the fate of exhaust products which are estimated to be retained in either the water phase or the atmosphere. The organic constituents scrubbed out by the water may stay there (soluble organics, for instance), or they may rise to the surface and evaporate. Inorganic materials (CO_2 and NO_2) are probably dissolved and retained in the water, although no sub-study was performed to prove it. Likewise, some constituents which make their way to the atmosphere may remain there, but others could remain close to the surface of the water and dissolve or condense later; the time factors which may be involved in these processes are simply not known.

A comparison of the impact estimates given in Table 18 to the most recent EPA National Inventory Data[9] is shown in Table 19. The inventory data, of course, are for air pollutants only, so the percentages in the columns at right are for atmospheric outboard emissions only. Emissions of aldehydes were not calculated on a mass basis because their overall impact would have been very low, probably about the same order of magnitude as NO_x. The concentration data on aldehydes should be sufficient for characterization purposes.

TABLE 19. COMPARISON OF OUTBOARD NATIONAL IMPACT ESTIMATES WITH EPA NATIONWIDE AIR POLLUTANT INVENTORY DATA

Contaminant	EPA Inventory Data 1970 10^6 tons/yr(9)		Outboard Atmospheric Estimates as % of	
	All Sources	Mobile Sources	All Sources	Mobile Sources
HC	34.7	19.5	0.893	1.59
CO	147.	111.	0.624	0.826
NO_x	22.7	11.7	0.0079	0.015
SO_x	33.9	1.0	0.0029	0.10

Although not necessary to the requirements of the present contract, it may be desirable at some point to estimate impact for outboards in some area other than the whole U. S. To this end, Table 20 has been prepared to facilitate calculations. It should be noted that factors expressed in each unit are rather heavily qualified, and that they are considered to progress from most accurate to least accurate in approximately the order shown. In other words, more facts instead of assumptions should lead to more accurate impact calculations.

In assessing impact, importance is attached not only to the mass emissions data, but also to the locales where and the times when the emissions are released. For outboards, a large majority of emissions undoubtedly occur in rural (rather than urban or suburban) areas, and during non-working hours (probably weighted heavily toward weekends).

TABLE 20. COMPOSITE EMISSION FACTORS FOR USE IN SMALL-SCALE OUTBOARD MOTOR IMPACT ESTIMATES (SUBJECT TO QUALIFICATIONS)

Emission Unit	Qualifications	Medium Affected	Exhaust Constituent				
			HC	CO	CO_2	NO_x	SO_x
g/hp hr	1, 2, 3	Atmos.	84.9	252.	388.	0.50	0.49
		Water	50.5	13.0	265.	0.092	0.027
		Total	135.	265.	653.	0.59	0.52
g/gal fuel	1, 2	Atmos.	503.	1,490.	2,300.	3.0	2.9
		Water	299.	76.9	1,570.	0.54	0.16
		Total	802.	1,570.	3,870.	3.5	3.1
g/motor hr	1, 2, 4	Atmos.	769.	2,280.	3,510.	4.5	4.4
		Water	457.	118.	2,400.	0.83	0.25
		Total	1,230.	2,400.	5,910.	5.3	4.6
kg/motor yr	1, 2, 4, 5	Atmos.	38.4	114.	176.	0.230	0.220
		Water	22.9	5.88	120.	0.042	0.012
		Total	61.3	120.	296.	0.270	0.230

List of Qualifications:

1. Based on Dec. 31, 1971 distribution of outboard motors in the U.S. by size
2. Based on experimental data generated under the subject program only.
3. Engine rated hp should be multiplied by applicable load factor before using this unit.
4. Based on 24.6 rated hp per motor and average load factor of 0.368
5. Based on 50 hr usage per year

The emissions are also undoubtedly seasonal, and the amounts emitted in each area will depend on the length of the boating season there as well as the concentration of boats. To make a seasonal/regional analysis possible, the U. S. will be divided into northern, central, and southern regions. The northern region is roughly between 49° and 43° N. latitude, the central region between 43° and 37°, and the southern region between 37° and 31°. States straddling the dividing lines will be placed

in the region containing the majority of their populations. In addition, the boating season will be assumed as 6 months in the northern region, 7 months in the central region, and 8 months in the southern region. An estimated distribution of outboard motors by state[4] is included as Appendix E, and it has been used in conjunction with the assumptions above to arrive at the breakdowns given in Table 21. According to this analysis, some 84% of all outboard emissions occur in the mid-summer months and 16% in the fall. About 15% appear to occur in the northern region, 47% in the central region, and 38% in the southern region. These results can be combined with the overall impact data to obtain mass emissions by season and region if such an analysis is desired.

TABLE 21. SUMMARY OF REGIONAL AND SEASONAL VARIATION OF OUTBOARD MOTOR EMISSIONS

Region	Percentage of Annual Emissions by Season				Regional Subtotals
	Dec.-Feb.	Mar.-May	Jun.-Aug.	Sep.-Nov.	
Northern	0.00	7.28	7.28	0.00	14.6
Central	0.00	20.2	20.2	6.76	47.2
Southern	0.00	14.4	14.4	9.58	38.3
Seasonal Subtotals	0.00	41.9	41.9	16.3	
Total			100.1		

A simplified analysis such as that just described has obvious inaccuracies, but it is still useful in determining overall usage and emission patterns. It is also interesting to note that well over half the outboards in use (3,902,000) are concentrated in the ten states having the largest motor populations. Motor concentrations seem to be highest in coastal states and those bordering the Great Lakes, which is quite logical. The three west coast states account for 10.4% of all outboards, three Gulf coast states (not including Mississippi and Alabama, which have only little coastline) account for 15.3%, and the eight states bordering the Great Lakes account for 37.6%. Taking into account the 17.1% of outboards in the Atlantic coast states (other than Florida and New York, already accounted for), only about 20% of outboards are in inland states. This is not to say that boats in states bordering large bodies of water are always operated offshore, because these same states also have numerous inland lakes, but the pattern of concentration around the country's borders is interesting.

VI. SUMMARY

This report covers a study of exhaust emissions from outboard motors, and it is Part 2 of a planned seven-part final report on "Exhaust Emissions from Uncontrolled Vehicles and Related Equipment Using Internal Combustion Engines," Contract No. EHS 70-108. It includes documentation and discussion on characterization of exhaust emissions from four water-cooled 2-stroke outboard motors (sections III and IV), and estimation of emission factors and national impact (section V). The testing was restricted to water-cooled 2-stroke engines because they dominate the field (estimates of the number of motors not in the category are 5% or less). As a part of the final report on the characterization phase of EHS 70-108, this report does not include information on aircraft turbine emissions, outboard motor crankcase drainage (except for qualitative mention), or locomotive emissions control technology. As required by the contract, these three latter areas have been or will be reported on separately.

Emissions tests on the four outboard motors; an OMC (Johnson) 4 hp, an OMC (Johnson) 9.5 hp, a Chrysler 35 hp, and a Mercury 65 hp; were conducted in the Emissions Research Laboratory on stationary test stands, with power absorption by eddy-current dynamometers connected to the propeller shafts. Emission concentrations were measured both before and after the exhaust gases were bubbled through water to determine amounts of exhaust constituents which remained in the water phase and which bubbled through into the atmosphere (subject to restrictions of the laboratory situation). Special tests were conducted with one engine to evaluate the effects of turbulence, bubble size, and water:exhaust gas ratio on the scrubbing of exhaust gases by the water.

Exhaust constituents measured were total hydrocarbons by FIA; NO_x and NO by chemiluminescence; hydrocarbons, CO, CO_2, and NO by NDIR; O_2 by electrochemical analyzer; aldehydes by wet chemistry; and light hydrocarbons by gas chromatograph. National impact was calculated for hydrocarbons, CO, CO_2, and NO_x for both the air and water phases. Expressing the atmospheric emissions from outboards as percentages of 1970 national totals from all sources[9], outboard hydrocarbons amounted to 0.893%, outboard CO was 0.624%, NO_x was 0.0079% and SO_x was 0.0029%. As percentages of mobile source emissions, outboard hydrocarbons were 1.59%, outboard CO was 0.826%, NO_x 0.015%, and outboard SO_x was 0.10%. Emissions of CO_2, while not relatable to available source inventories, may be of more interest from a water pollution standpoint than from an air pollution standpoint. Regarding the regional aspects of pollution from outboards, it is estimated that about 15% occurs in the northern third of the country, 47% in the central third, and 38% in the southern third. Estimates of motor populations by state also show that about 80% of outboards are concentrated in states bordering the oceans or the Great Lakes, but the fraction of operating time spent offshore as compared to that spent on inland waters is not known.

To make a more accurate assessment of outboard emissions, additional testing including some newer types of engines would be required. It would also be of interest to include a rotary outboard such as those manufactured by Yanmar of Japan, because it is likely that Wankels will soon find application in outboards. Another refinement could be added by conducting some sort of usage survey, perhaps with simple hour meters connected to engines running in various places around the country, to make the utilization numbers more accurate for various size classes of motors.

Although it was not an objective of this project, work should be done to define the mixing of exhaust gases and water in the real situation more precisely. This work might initially involve underwater photography of a number of engine/propeller/hull/speed combinations to determine a range of bubble sizes and residence times and some kind of a turbulence index. That information could then serve as basis for design of a fluid dynamic simulator which could be used for further studies. An additional study to determine characteristics of a number of lakes and rivers (temperature, pH, etc.) would serve to shed more light on the chemistry of the mass transfer process.

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APPENDIX A

EMISSIONS DATA ON A JOHNSON 4R71 ENGINE

TEST DATA ON JOHNSON 4R71 OUTBOARD MOTOR
1/4/72 – 1/27/72 11-2869-01

	FIA HYDROCARBONS, ppm C $\times 10^{-4}$ (WET)							
	RUN NUMBER							AVERAGE OR TYPICAL VALUE
MODE	5	6	7	8	9	10	11	
1	4.92	5.34	———	———	5.04	5.48	5.24	5.20
1 A	4.20	3.96	———	———	3.28	4.44	5.12	4.20
2	4.20	4.88	———	———	4.00	4.48	4.24	4.36
2 A	3.76	3.72	———	———	2.52	3.20	3.72	3.38
3	3.64	4.76	3.70	3.63	3.58	4.04	3.98	3.90
3 A	3.36	4.00	2.72	2.84	2.48	2.68	2.80	2.98
4	5.32	5.64	5.08	———	5.00	4.56	5.18	5.13
4 A	3.12	4.44	3.48	———	3.40	3.04	3.72	3.53
5	———	5.72	———	6.24	8.00	6.32	8.10	6.88
5 A	———	3.92	———	5.20	6.48	4.08	6.16	5.17
6	———	7.20	9.28	8.12	9.72	8.56	———	8.58
6 A	———	6.24	6.40	6.08	6.56	6.24	———	6.30

	NDIR HYDROCARBONS, ppm C $\times 10^{-4}$ (WET)							
	RUN NUMBER							AVERAGE OR TYPICAL VALUE
MODE	5	6	7	8	9	10	11	
1	———	———	3.40	2.80	3.01	2.97	3.89	3.21
1 A	———	———	4.02	3.11	3.24	3.53	3.53	3.49
2	———	2.15	2.29	2.48	2.12	2.67	2.48	2.36
2 A	———	2.65	2.70	1.97	2.32	2.66	2.99	2.55
3	———	2.40	2.41	2.12	2.00	2.52	2.40	2.31
3 A	———	2.65	2.11	2.75	2.04	2.71	2.55	2.47
4	———	2.63	3.19	2.61	2.58	3.11	3.02	2.86
4 A	———	2.86	3.23	1.97	2.87	3.18	3.24	2.89
5	———	———	4.18	3.51	4.56	4.67	5.57	4.50
5 A	———	———	5.42	5.43	4.55	3.12	5.75	4.85
6	———	———	5.99	6.84	5.50	6.58	7.21	6.42
6 A	———	———	6.44	7.30	5.75	6.46	8.09	6.81

TEST DATA ON JOHNSON 4R71 OUTBOARD MOTOR
1/4/72 - 1/27/72 11-2869-01

	NDIR CO, VOLUME % (WET)							
	RUN NUMBER							AVERAGE OR TYPICAL VALUE
MODE	5	6	7	8	9	10	11	
1	———	3.34	3.11	———	2.20	4.33	2.63	3.12
1 A	———	2.88	3.48	———	2.43	4.05	3.12	3.19
2	———	4.30	3.24	———	3.42	4.67	———	3.91
2 A	———	4.52	3.11	———	3.30	3.83	———	3.69
3	———	5.66	3.67	———	3.96	3.98	———	4.32
3 A	———	5.23	4.13	———	4.21	3.94	———	4.38
4	———	5.19	4.93	4.78	5.10	3.49	3.97	4.58
4 A	———	5.74	5.48	4.99	5.24	3.64	4.25	4.89
5	———	5.47	5.36	5.95	5.61	4.80	4.79	5.33
5 A	———	5.88	5.88	6.46	5.70	4.71	4.58	5.54
6	———	5.69	5.52	5.13	5.34	4.86	4.61	5.19
6 A	———	6.16	6.02	5.36	5.37	4.82	4.64	5.40

	NDIR CO_2, VOLUME % (WET)							
	RUN NUMBER							AVERAGE OR TYPICAL VALUE
MODE	5	6	7	8	9	10	11	
1	8.65	7.70	5.86	8.33	8.06	6.78	7.49	7.55
1 A	5.68	4.38	6.07	6.00	6.40	6.17	6.16	5.84
2	8.75	7.79	9.31	8.42	7.97	7.84	8.57	8.38
2 A	5.18	5.76	7.43	6.54	6.72	5.20	7.20	6.29
3	8.62	6.23	7.73	7.87	7.68	7.51	8.96	7.80
3 A	6.53	3.83	6.86	6.00	6.48	6.09	7.38	6.17
4	———	7.12	7.63	6.66	6.72	7.54	7.39	7.18
4 A	———	4.48	5.83	4.90	5.64	5.56	4.43	5.14
5	———	6.23	5.75	5.42	5.38	5.89	5.51	5.70
5 A	———	4.89	5.03	4.23	4.57	5.64	4.56	4.82
6	———	4.96	5.56	4.89	4.69	5.11	5.23	5.07
6 A	———	4.35	4.41	4.35	3.28	4.10	4.36	4.14

TEST DATA ON JOHNSON 4R71 OUTBOARD MOTOR
1/4/72 – 1/27/72 11-2869-01

	CHEMILUMINESCENT NO_x, ppm (WET)							
	RUN NUMBER							AVERAGE OR TYPICAL VALUE
MODE	5	6	7	8	9	10	11	
1	———	139	134	———	244	88	143	150
1 A	———	76	116	———	201	124	116	127
2	———	37	39	———	74	50	54	51
2 A	———	41	55	———	76	43	53	54
3	34	14	29	38	43	43	32	33
3 A	37	20	33	42	51	41	31	36
4	———	26	15	18	19	21	18	20
4 A	———	28	14	24	15	22	18	20
5	———	7.1	5.3	7.1	8.9	6.2	5.3	6.6
5 A	———	8.8	2.9	7.8	3.9	2.9	3.9	5.0
6	———	5.4	5.3	4.5	9.9	6.2	6.2	6.2
6 A	———	3.9	3.9	2.9	3.9	2.9	3.9	3.6

	CHEMILUMINESCENT NO, ppm (WET)							
	RUN NUMBER							AVERAGE OR TYPICAL VALUE
MODE	5	6	7	8	9	10	11	
1	———	122	113	———	197	70	117	124
1 A	———	61	115	———	167	90	122	111
2	———	32	35	———	67	42	46	44
2 A	———	35	49	———	71	41	51	49
3	30	12	32	35	39	37	29	31
3 A	32	16	33	39	47	39	29	34
4	———	21	11	14	14	19	16	16
4 A	———	23	12	19	15	20	16	18
5	———	6.2	3.6	5.3	3.6	2.7	3.6	4.2
5 A	———	8.8	2.9	7.8	2.9	2.0	2.9	4.6
6	———	4.5	5.3	3.6	3.6	2.7	3.6	3.9
6 A	———	3.9	3.9	3.9	2.9	2.0	2.9	3.2

TEST DATA ON JOHNSON 4R71 OUTBOARD MOTOR
1/4/72 – 1/27/72 11-2869-01

	NDIR NO, ppm (WET)							
	RUN NUMBER							AVERAGE OR TYPICAL VALUE
MODE	5	6	7	8	9	10	11	
1	———	159	174	———	———	111	158	150
1A	———	100	179	———	———	131	163	143
2	123	76	93	———	———	81	115	98
2A	117	84	131	———	———	84	108	105
3	83	69	91	84	———	82	115	87
3A	84	76	92	92	———	84	108	89
4	72	65	65	55	———	72	72	67
4A	59	68	61	61	———	69	69	64
5	91	55	59	42	———	58	73	63
5A	76	61	68	53	———	61	61	63
6	73	70	77	60	———	80	116	79
6A	68	68	76	61	———	69	116	76

	POLAROGRAPHIC O_2, VOLUME % (WET)							
	RUN NUMBER							AVERAGE OR TYPICAL VALUE
MODE	5	6	7	8	9	10	11	
1	7.6	———	6.6	6.8	———	4.4	4.9	6.1
1A	9.3	———	7.3	8.1	———	5.4	6.4	7.3
2	6.0	5.1	4.6	5.6	4.9	3.5	4.2	5.9
2A	6.6	7.8	5.6	6.7	6.4	6.2	5.9	6.5
3	5.1	4.8	4.9	4.8	4.2	3.7	4.0	4.5
3A	6.1	5.4	5.2	5.7	6.1	4.7	5.4	5.5
4	6.6	5.4	4.9	5.2	4.9	3.8	4.2	5.0
4A	7.8	6.4	5.4	6.0	6.7	5.1	5.7	6.2
5	6.2	5.5	6.7	6.6	———	4.5	5.4	5.8
5A	7.7	6.3	7.7	7.3	———	6.4	6.9	7.0
6	6.5	7.5	7.7	7.2	———	5.3	5.9	6.7
6A	7.7	8.4	8.6	8.1	———	6.7	7.4	7.8

TEST DATA ON JOHNSON 4R71 OUTBOARD MOTOR
1/4/72 – 1/27/72 11-2869-01

	FUEL CONSUMPTION, lb/hr (NORMAL AND "A" MODES)							
	RUN NUMBER							AVERAGE OR TYPICAL VALUE
MODE	5	6	7	8	9	* 10	* 11	
1				4.11	4.04	3.34	3.42	4.08 / *3.38
1 A								
2				2.76	2.80	2.61	2.58	2.78 / *2.60
2 A								
3				1.94	1.87	1.82	2.04	1.92
3 A								
4				1.25	1.19	1.16	1.29	1.22
4 A								
5				1.00	1.07	0.93	1.05	1.01
5 A								
6				0.90	0.97	0.98	0.98	0.96
6 A								

* NEW FUEL PUMP INSTALLED PRIOR TO RUN 10

	FUEL CONSUMPTION, g/hr (NORMAL AND "A" MODES)							
	RUN NUMBER							AVERAGE OR TYPICAL VALUE
MODE	5	6	7	8	9	* 10	* 11	
1				1870	1830	1520	1550	1850 / *1530
1 A								
2				1250	1270	1180	1170	1260 / *1180
2 A								
3				880	848	825	925	870
3 A								
4				567	539	526	585	553
4 A								
5				454	485	422	476	458
5 A								
6				408	440	445	445	435
6 A								

APPENDIX B

EMISSIONS DATA ON A JOHNSON 9R72 ENGINE

TEST DATA ON JOHNSON 9.5 hp OUTBOARD MOTOR

	FIA HYDROCARBONS, ppmC $\times 10^{-4}$ (WET)								
	RUN NUMBER								AVERAGE OR TYPICAL VALUE
MODE	1	2	3	4	5	6	7	8	
1	3.30	3.42	3.46	3.30	3.54	3.00	3.60	3.20	3.35
1A	2.68	2.08	2.16	2.08	2.48	2.44	2.56	2.16	2.33
2	2.84	4.04	4.04	3.68	4.04	3.56	4.04	3.92	3.77
2A	1.52	2.72	2.28	2.20	2.52	2.40	2.56	2.48	2.33
3	3.48	5.56	4.90	4.64	5.12	4.88	5.04	5.00	4.82
3A	1.92	2.88	2.80	2.88	3.36	3.12	3.36	3.04	2.92
4	6.81	7.12	5.72	5.12	5.94	5.72	5.88	6.16	6.05
4A	3.49	3.44	3.20	2.92	3.60	3.58	3.60	3.68	3.43
5	9.78	8.64	6.08	5.16	9.44	10.08	8.60	8.76	8.31
5A	5.33	4.48	3.44	2.80	5.60	5.84	4.48	5.04	4.62
6	10.22	9.36	7.56	6.56	11.04	12.56	10.92	10.32	9.82
6A	5.42	4.64	4.16	3.76	6.56	7.52	6.48	6.24	5.59

	NDIR HYDROCARBONS, ppmC $\times 10^{-4}$ (WET)								
	RUN NUMBER								AVERAGE OR TYPICAL VALUE
MODE	1	2	3	4	5	6	7	8	
1	2.36	1.99	1.78	1.30	2.33		1.90	1.88	1.93
1A	2.31	——	2.41	1.72	2.71		2.27	1.88	2.22
2	2.92	2.83	1.97	1.90	2.30		1.93	1.90	2.25
2A	3.58	3.52	2.23	1.85	2.71		2.15	2.60	2.66
3	3.41	3.12	2.01	2.64	2.84		2.45	2.63	2.73
3A	3.66	4.03	2.23	2.60	3.84		2.55	1.72	2.95
4	4.26	3.33	2.66	2.85	3.26		2.95	2.82	3.16
4A	4.94	4.45	3.07	2.82	3.35		3.42	2.83	3.55
5	4.73	4.27	2.87	2.58	4.31		3.26	3.16	3.60
5A	4.23	4.23	3.21	2.82	4.45		3.99	2.83	3.68
6	5.40	4.85	3.00	3.46	5.25		5.10	3.91	4.42
6A	5.85	5.85	4.03	3.84	6.22		4.45	4.45	4.95

TEST DATA ON JOHNSON 9.5 hp OUTBOARD MOTOR

	NDIR CO, VOLUME % (WET)								
	RUN NUMBER								AVERAGE OR TYPICAL VALUE
MODE	1	2	3	4	5	6	7	8	
1	4.36	4.45	4.32	4.23	4.22	4.68	4.68	5.01	4.49
1A	4.83	4.83	4.83	4.70	4.83	5.62	5.08	5.76	5.06
2	3.64	4.13	3.62	3.34	3.42	4.30	4.26	4.34	3.88
2A	4.23	4.59	3.90	4.23	3.90	4.46	4.35	4.95	4.32
3	4.22	4.77	4.19	3.77	4.15	4.78	4.37	4.72	4.37
3A	4.70	5.22	4.46	4.12	4.77	5.22	5.15	5.35	4.87
4	4.75	4.73	3.88	3.89	4.14	5.04	4.45	4.80	4.46
4A	5.08	5.22	4.46	4.12	4.53	5.49	4.83	5.35	4.88
5	5.08	5.20	3.56	2.75	5.17	5.44	5.16	5.26	4.70
5A	5.48	5.62	3.79	3.10	5.48	5.70	5.22	5.70	5.01
6	4.45	4.81	3.68	3.26	4.63	4.85	4.65	4.95	4.41
6A	4.83	4.83	4.35	3.59	5.08	4.96	5.15	5.28	4.75

	NDIR CO_2, VOLUME % (WET)								
	RUN NUMBER								AVERAGE OR TYPICAL VALUE
MODE	1	2	3	4	5	6	7	8	
1	7.73	7.88	7.87	7.91	7.84	7.72	7.72	7.46	7.76
1A	5.13	5.41	5.41	5.71	5.57	5.78	5.71	5.13	5.48
2	7.72	7.75	8.00	8.10	7.89	7.67	7.94	7.42	7.81
2A	5.41	4.99	5.13	5.41	5.27	5.71	5.49	5.34	5.34
3	6.89	6.81	7.20	7.30	6.90	6.67	7.18	6.71	6.95
3A	4.58	4.71	4.98	4.71	4.98	5.28	5.06	4.91	4.90
4	6.19	6.31	6.90	6.92	6.57	6.27	6.77	6.22	6.51
4A	4.58	3.92	4.84	4.33	4.84	4.99	5.06	4.71	4.66
5	5.29	5.22	6.73	7.45	4.91	4.64	5.48	5.14	5.60
5A	4.04	3.67	4.98	4.98	3.66	3.24	4.44	3.72	4.09
6	5.29	4.73	6.23	6.48	4.50	4.04	4.69	4.72	5.08
6A	3.79	3.42	4.31	3.92	3.41	3.06	3.67	3.72	3.66

TEST DATA ON JOHNSON 9.5 hp OUTBOARD MOTOR

	CHEMILUMINESCENT NOx, ppm (WET)								
	RUN NUMBER								AVERAGE OR TYPICAL VALUE
MODE	1	2	3	4	5	6	7	8	
1	86	75	78	95	80	71	78	75	80
1A	92	76	85	104	91	79	87	76	86
2	53	55	52	58	57	52	50	55	53
2A	55	56	56	55	58	57	53	56	56
3	31	32	30	39	34	32	31	32	33
3A	31	31	30	34	33	31	28	31	31
4	40	19	17	19	19	16	18	19	21
4A	39	15	16	19	17	15	17	15	19
5	13	5.9	5.1	6.4	3.5	7.1	6.6	5.9	6.7
5A	10	3.6	4.8	6.7	1.9	5.3	4.4	3.6	5.0
6	14	6.2	5.3	6.6	3.5	7.2	6.9	6.2	6.9
6A	12	4.3	4.8	5.3	2.9	5.3	4.8	4.3	5.4

	CHEMILUMINESCENT NO, ppm (WET)								
	RUN NUMBER								AVERAGE OR TYPICAL VALUE
MODE	1	2	3	4	5	6	7	8	
1	80	75	69	87	72	66	72	66	73
1A	73	78	81	99	82	75	74	76	80
2	48	42	47	49	52	47	45	48	47
2A	55	48	53	53	53	55	51	52	53
3	27	24	27	28	28	27	27	27	27
3A	31	24	26	31	31	29	27	29	29
4	28	13	15	16	15	14	15	14	16
4A	31	12	15	16	16	15	16	15	17
5	7.0	3.9	3.5	4.8	2.0	4.9	3.9	4.2	4.2
5A	5.8	2.4	2.9	4.8	1.9	3.9	2.9	2.9	3.4
6	9.0	3.1	4.2	4.4	2.6	5.5	5.1	5.1	4.9
6A	6.7	2.9	1.5	3.8	1.9	4.4	3.9	3.8	3.6

TEST DATA ON JOHNSON 9.5 hp OUTBOARD MOTOR

	NDIR NO, ppm (WET)								
	RUN NUMBER								AVERAGE OR TYPICAL VALUE
MODE	1	2	3	4	5	6	7	8	
1	116	90	115	122	103	81	90	85	100
1A	94	107	136	128	94	101	101	87	106
2	110	78	109	103	63	75	81	79	87
2A	107	80	107	94	60	80	80	87	87
3	98	79	67	98	57	70	76	73	77
3A	94	80	67	94	53	74	67	67	75
4	86	79	73	82	18	58	64	58	65
4A	80	80	67	67	14	60	67	53	61
5	42	76	61	61	37	52	52	42	53
5A	53	67	53	53	26	53	46	46	50
6	71	37	49	74	49	75	62	68	61
6A	60	40	——	67	60	74	60	80	63

	ELECTROCHEMICAL O_2, VOLUME % (WET)								
	RUN NUMBER								AVERAGE OR TYPICAL VALUE
MODE	1	2	3	4	5	6	7	8	
1	3.6	3.8	3.6	3.5	3.6	3.7	3.9	3.5	3.6
1A	4.6	4.4	4.2	4.3	4.6	4.2	4.6	4.3	4.4
2	3.9	4.3	3.7	4.3	4.0	4.2	4.3	4.2	4.1
2A	4.6	4.9	4.9	5.3	5.1	5.3	5.3	5.3	5.1
3	5.1	5.5	4.8	5.3	5.0	5.0	5.3	5.1	5.1
3A	5.9	6.1	5.8	6.3	6.0	5.8	5.8	6.0	5.9
4	5.5	5.5	5.2	5.5	5.5	5.4	5.5	5.7	5.5
4A	6.5	5.0	5.4	6.8	6.4	6.3	6.4	6.5	6.3
5	6.6	7.0	6.0	6.0	7.4	7.4	6.7	6.8	6.7
5A	7.7	7.6	6.9	6.8	8.4	8.2	7.1	8.0	7.6
6	7.5	8.0	6.7	6.8	8.4	8.3	7.9	7.7	7.7
6A	8.3	9.3	7.8	7.8	9.5	9.5	8.6	8.7	8.7

TEST DATA ON JOHNSON 9.5 hp OUTBOARD MOTOR

	FUEL CONSUMPTION, lbm/hr								
	RUN NUMBER								AVERAGE OR TYPICAL VALUE
MODE	1	2	3	4	5	6	7	8	
1	8.17	8.11	8.34	8.09	7.81	8.08	7.95	8.37	8.11
1A	8.05	8.19	8.37	8.14	7.86	8.17	8.00	8.37	8.14
2	7.43	7.46	7.52	7.09	7.22	7.35	7.36	7.31	7.35
2A	7.43	7.57	7.54	7.05	7.22	7.20	7.38	7.38	7.35
3	6.17	6.06	6.33	5.91	5.88	6.18	6.27	5.96	6.09
3A	6.19	6.19	6.37	5.90	5.86	6.19	6.30	5.97	6.12
4	4.08	4.11	3.94	3.80	3.74	4.09	4.18	3.74	3.96
4A	4.09	4.11	4.07	3.73	3.64	4.07	4.13	3.73	3.95
5	2.18	1.95	1.99	1.60	2.21	2.25	2.00	2.11	2.03
5A	2.18	1.98	1.93	1.55	2.32	2.20	2.01	2.10	2.03
6	1.68	1.85	1.59	1.56	1.76	1.75	1.85	1.88	1.74
6A	1.83	1.80	1.63	1.52	1.71	1.77	1.84	1.86	1.75

	FUEL CONSUMPTION, g/hr								
	RUN NUMBER								AVERAGE OR TYPICAL VALUE
MODE	1	2	3	4	5	6	7	8	
1	3710	3680	3780	3670	3540	3670	3600	3800	3680
1A	3660	3720	3800	3690	3570	3710	3630	3800	3700
2	3370	3390	3420	3220	3280	3340	3340	3320	3330
2A	3370	3430	3420	3200	3280	3260	3350	3350	3330
3	2800	2750	2870	2680	2670	2800	2850	2700	2770
3A	2810	2810	2890	2680	2660	2810	2860	2710	2780
4	1850	1870	1790	1730	1700	1860	1900	1700	1800
4A	1860	1870	1850	1690	1650	1850	1870	1690	1790
5	990	886	904	724	1000	1020	910	960	925
5A	990	901	875	705	1050	1000	914	955	924
6	764	840	723	706	797	797	839	855	790
6A	839	818	740	691	777	803	834	845	793

APPENDIX C

EMISSIONS DATA ON A CHRYSLER 356HA ENGINE

TEST DATA ON CHRYSLER 35 hp OUTBOARD MOTOR

	FIA HYDROCARBONS, ppm C x 10^{-4} (WET) RUN NUMBER							AVERAGE OR TYPICAL VALUE	
MODE	1	2	3	4	5	6	7	1-5	6 & 7
1	4.08	4.00	3.44	4.68	5.44	——	——	4.32	——
1A	2.40	3.04	2.40	3.08	3.84	——	——	2.95	——
2	3.88	3.76	3.40	4.38	5.04	3.62	3.60	4.09	3.61
2A	2.56	2.72	2.16	3.12	3.52	2.52	2.42	2.82	2.47
3	4.62	3.64	4.46	5.08	6.32	4.08	4.34	4.82	4.21
3A	3.04	2.48	2.96	3.60	4.48	3.04	2.76	3.31	2.90
4	5.28	3.72	5.22	5.28	6.56	5.60	5.30	5.21	5.45
4A	3.76	2.40	3.48	3.60	4.48	3.74	3.36	3.54	3.55
5	7.12	5.12	7.96	8.24	9.00	8.64	7.88	7.49	8.26
5A	4.96	3.44	5.60	5.60	5.60	5.92	5.28	5.04	5.60
6	10.12	7.44	10.96	10.40	11.84	——	——	10.15	——
6A	7.12	4.48	8.92	7.04	7.44	——	——	7.00	——

	NDIR HYDROCARBONS, ppm C x 10^{-4} (WET) RUN NUMBER							AVERAGE OR TYPICAL VALUE	
MODE	1	2	3	4	5	6	7	1-5	6 & 7
1	1.85	1.61	1.80	2.06	1.67	——	——	1.80	——
1A	1.49	1.88	1.88	2.50	2.03	——	——	1.96	——
2	1.94	1.49	1.93	1.88	1.29	1.82	1.52	1.71	1.67
2A	2.14	1.63	2.23	2.23	1.49	2.10	1.85	1.94	1.98
3	1.48	1.36	1.92	2.35	1.75	2.11	1.63	1.77	1.87
3A	2.02	1.66	1.88	2.94	1.88	2.27	1.69	2.08	1.98
4	1.82	1.41	2.41	2.55	1.34	2.52	2.17	1.91	234
4A	2.06	1.66	2.60	3.20	1.60	2.41	2.40	2.22	2.41
5	2.30	1.70	4.81	4.89	2.79	3.80	4.41	3.30	4.11
5A	2.82	2.06	5.67	5.67	3.00	4.22	5.21	3.84	4.03
6	3.50	2.48	6.22	5.65	3.80	——	——	4.33	——
6A	3.93	2.82	7.31	7.58	3.87	——	——	5.10	——

TEST DATA ON CHRYSLER 35 hp OUTBOARD MOTOR

	NDIR CO, VOLUME % (WET)							AVERAGE OR TYPICAL VALUE	
	RUN NUMBER								
MODE	1	2	3	4	5	6	7	1-5	6 & 7
1	6.40	7.38	6.92	7.18	6.71	——	——	6.92	——
1A	7.11	8.34	7.84	8.33	7.55	——	——	7.83	——
2	5.82	5.89	6.11	6.92	6.77	6.98	6.86	6.30	6.92
2A	6.36	6.68	6.68	7.75	7.65	7.84	7.75	7.02	7.80
3	6.06	5.38	6.17	6.57	6.68	6.75	6.72	6.17	6.74
3A	7.20	6.20	6.85	7.46	7.47	7.46	7.51	7.04	7.49
4	5.08	5.02	6.22	6.24	6.13	6.32	6.28	5.74	6.30
4A	5.76	5.61	6.84	6.84	6.68	6.90	7.02	6.35	6.96
5	5.16	4.71	5.64	5.66	5.64	5.39	5.26	5.36	5.32
5A	5.61	5.08	6.13	6.20	6.20	5.75	5.83	5.84	5.79
6	4.76	4.85	5.05	4.94	4.92	——	——	4.90	——
6A	5.21	5.27	5.47	5.27	5.27	——	——	5.30	——

	NDIR CO_2, VOLUME % (WET)							AVERAGE OR TYPICAL VALUE	
	RUN NUMBER								
MODE	1	2	3	4	5	6	7	1-5	6 & 7
1	6.35	6.08	6.53	6.17	6.68	——	——	6.36	——
1A	4.57	4.91	4.84	4.17	4.43	——	——	4.58	——
2	6.59	6.94	7.26	6.52	6.74	6.69	6.78	6.81	6.74
2A	4.57	5.05	5.05	4.70	4.97	4.90	4.70	4.87	4.80
3	6.77	6.06	6.25	6.44	6.40	6.46	6.50	6.38	6.48
3A	4.43	4.64	4.23	4.29	4.30	4.30	4.77	4.38	4.54
4	6.64	7.00	6.15	6.35	6.51	6.10	5.88	6.53	5.99
4A	4.43	5.40	4.03	4.03	4.10	4.17	4.23	4.40	4.20
5	5.82	6.88	5.40	5.58	5.52	5.03	5.21	5.84	5.43
5A	4.03	4.70	3.90	3.79	3.84	3.59	3.66	4.05	3.62
6	5.14	5.52	4.75	4.96	4.85	——	——	5.04	——
6A	3.84	3.79	3.50	3.29	3.17	——	——	3.52	——

TEST DATA ON CHRYSLER 35 hp OUTBOARD MOTOR

	CHEMILUMINESCENT NOx, ppm (WET) RUN NUMBER							AVERAGE OR TYPICAL VALUE	
MODE	1	2	3	4	5	6	7	1-5	6&7
1	52	40	46	35	48	——	——	44	——
1A	50	36	41	26	40	——	——	39	——
2	50	51	48	39	43	41	42	46	42
2A	48	46	43	29	35	27	29	40	28
3	36	30	36	32	33	33	35	33	34
3A	21	19	27	20	19	17	18	21	18
4	28	29	27	22	26	24	19	26	22
4A	19	26	17	12	16	8.6	10	18	9
5	18	14	18	16	18	18	18	17	18
5A	7.2	8.7	5.3	2.5	5.3	3.9	3.0	5.8	3.4
6	18.	16	19	15	18	——	——	17	——
6A	5.7	4.8	5.8	1.9	5.3	——	——	4.7	——

	CHEMILUMINESCENT NO, ppm (WET) RUN NUMBER							AVERAGE OR TYPICAL VALUE	
MODE	1	2	3	4	5	6	7	1-5	6&7
1	43	28	42	24	36	——	——	35	——
1A	46	31	41	21	37	——	——	35	——
2	40	42	38	25	30	24	27	35	26
2A	43	40	40	26	33	21	28	36	24
3	22	19	23	16	18	16	18	20	17
3A	19	18	24	17	19	16	17	19	16
4	19	22	15	15	15	10	10	17	10
4A	18	24	15	11	15	8.6	9.0	17	8.8
5	5.6	5.9	4.6	2.6	5.3	5.3	5.0	4.8	5.1
5A	4.8	5.7	3.9	1.2	3.9	3.9	3.0	3.9	3.5
6	6.4	4.0	6.0	3.5	6.2	——	——	5.2	——
6A	5.3	2.4	4.8	1.2	4.3	——	——	3.6	——

TEST DATA ON CHRYSLER 35 hp OUTBOARD MOTOR

	NDIR NO, ppm (WET)							AVERAGE OR TYPICAL VALUE	
	RUN NUMBER								
MODE	1	2	3	4	5	6	7	1-5	6&7
1	50	83	53	62	77	——	——	65	——
1A	46	87	60	67	80	——	——	68	——
2	47	96	81	71	68	89	71	73	80
2A	53	100	73	73	67	94	67	73	81
3	51	98	90	80	71	80	83	78	87
3A	40	100	80	80	73	80	73	75	76
4	69	63	72	72	60	92	77	67	84
4A	53	67	73	67	60	80	73	64	76
5	45	70	73	76	70	102	86	67	94
5A	40	67	67	60	73	80	67	61	74
6	61	98	80	83	80	——	——	80	——
6A	53	80	73	73	80	——	——	72	——

	ELECTROCHEMICAL O_2, VOLUME % (WET)							AVERAGE OR TYPICAL VALUE	
	RUN NUMBER								
MODE	1	2	3	4	5	6	7	1-5	6&7
1	3.7	3.2	3.4	3.5	3.3	——	——	3.4	——
1A	4.8	3.9	4.6	4.2	4.1	——	——	4.3	——
2	3.2	3.1	3.3	3.2	3.1	3.1	2.9	3.2	3.0
2A	4.1	3.9	4.0	3.9	3.9	3.6	3.7	4.0	3.6
3	3.5	4.4	3.6	3.6	4.0	3.5	3.4	3.8	3.4
3A	4.4	4.8	4.8	4.4	5.4	4.4	4.2	4.8	4.3
4	3.9	4.0	4.1	4.2	4.4	4.8	4.8	4.1	4.8
4A	4.7	4.8	5.3	5.2	4.9	5.8	5.6	5.0	5.7
5	5.2	4.6	5.9	4.9	4.8	6.9	6.9	5.1	6.9
5A	5.7	5.2	6.7	5.5	5.3	7.8	8.0	5.7	7.9
6	6.6	5.8	6.9	5.4	5.2	——	——	6.0	——
6A	7.2	6.9	8.2	5.7	5.8	——	——	6.8	——

TEST DATA ON CHRYSLER 35 hp OUTBOARD MOTOR

	FUEL CONSUMPTION, lbm/hr							AVERAGE OR TYPICAL VALUE	
	RUN NUMBER								
MODE	1	2	3	4	5	6	7	1-5	6&7
1	26.0	27.0	25.6	25.8	25.0	——	——	25.9	——
1A	25.8	26.8	26.3	25.8	25.0	——	——	25.7	——
2	16.9	16.8	16.8	18.0	17.2	17.2	17.2	17.1	17.2
2A	17.0	17.0	17.0	17.9	17.5	17.4	17.3	17.2	17.4
3	12.4	12.3	11.8	12.7	12.5	12.2	12.4	12.3	12.3
3A	12.3	12.2	12.1	12.6	12.5	12.1	12.5	12.3	12.3
4	7.26	7.28	7.88	7.95	7.94	7.88	7.85	7.66	7.86
4A	7.44	7.32	7.92	7.85	7.92	7.92	7.85	7.69	7.88
5	3.79	3.71	4.33	4.48	4.25	4.55	4.49	4.11	4.44
5A	3.89	3.61	4.33	4.41	4.17	4.52	4.34	4.08	4.51
6	4.17	3.93	4.94	4.90	4.58	——	——	4.51	——
6A	4.24	4.00	4.92	4.86	4.58	——	——	4.52	——

	FUEL CONSUMPTION, g/hr							AVERAGE OR TYPICAL VALUE	
	RUN NUMBER								
MODE	1	2	3	4	5	6	7	1-5	6&7
1	11,800	12,200	11,600	11,700	11,400	——	——	11,750	——
1A	11,700	12,200	11,500	11,700	11,300	——	——	11,670	——
2	7660	7620	7590	8170	7810	7820	7800	7770	7810
2A	7700	7700	7640	8120	7930	7900	7850	7820	7870
3	5640	5570	5360	5750	5680	5520	5610	5600	5560
3A	5580	5510	5470	5790	5660	5480	5660	5580	5570
4	3290	3300	3570	3610	3600	3570	3590	3480	3570
4A	3380	3320	3590	3560	3590	3590	3560	3490	3580
5	1720	1680	1960	2030	1930	2060	1970	1860	2020
5A	1770	1640	1970	2000	1890	2050	2040	1850	2040
6	1890	1780	2240	2220	2080	——	——	2040	——
6A	1920	1820	2230	2210	2080	——	——	2050	——

APPENDIX D

EMISSIONS DATA ON A MERCURY 650 ENGINE

TEST DATA ON MERCURY 650 OUTBOARD MOTOR

2/21/72 - 2/28/72 11-2869-01

	FIA HYDROCARBONS, ppm C $\times 10^{-4}$ (WET)					
	RUN NUMBER					AVERAGE OR TYPICAL VALUE
MODE	2	3	4	5	6	
1	4.32	3.82	4.68	4.86	4.68	4.47
1 A	3.48	2.56	3.04	3.12	3.40	3.12
2	4.14	4.04	4.00	4.44	4.00	4.12
2 A	3.30	3.12	2.56	4.44	2.80	3.24
3	3.50	4.20	3.53	3.74	3.74	3.74
3 A	2.96	2.76	2.28	2.56	2.56	2.62
4	2.99	3.56	5.16	4.86	4.46	4.23
4 A	2.20	2.60	3.92	3.80	2.32	2.97
5	5.96	5.06	6.00	5.88	5.88	5.76
5 A	4.80	3.72	4.64	4.64	4.64	4.49
6	7.26	6.52	7.22	6.96	6.94	6.98
6 A	5.92	5.04	5.84	5.88	5.60	5.66
7	7.88	7.22	8.04	7.96	8.08	7.84
7 A	6.60	5.52	7.20	6.80	6.76	6.58

	NDIR HYDROCARBONS, ppm C $\times 10^{-4}$ (WET)					
	RUN NUMBER					AVERAGE OR TYPICAL VALUE
MODE	2	3	4	5	6	
1	2.64	3.21	——	——	3.35	3.07
1 A	2.81	3.77	——	——	2.60	3.06
2	2.50	3.04	——	——	3.14	2.89
2 A	2.45	3.24	——	——	3.17	2.95
3	2.14	2.41	——	——	1.88	2.14
3 A	2.15	2.65	——	——	1.89	2.23
4	3.15	3.01	——	——	3.14	3.10
4 A	2.50	3.77	——	——	3.45	3.24
5	——	4.89	——	——	4.41	4.65
5 A	——	5.15	——	——	4.77	4.96
6	——	——	——	——	5.63	5.63
6 A	——	——	——	——	5.91	5.91
7	——	——	——	——	——	——
7 A	——	——	——	——	——	——

TEST DATA ON MERCURY 650 OUTBOARD MOTOR

2/21/72 - 2/28/72

11-2869-01

	NDIR CO, VOLUME % (WET)					
	RUN NUMBER					AVERAGE OR TYPICAL VALUE
MODE	2	3	4	5	6	
1	2.80	3.26	3.19	3.22	3.10	3.11
1 A	3.44	3.58	3.53	3.48	3.48	3.50
2	2.54	2.76	2.66	2.84	2.72	2.70
2 A	2.85	2.94	3.02	3.20	3.06	3.01
3	3.38	3.52	3.56	3.27	3.34	3.41
3 A	3.78	3.94	3.98	3.78	3.83	3.86
4	5.00	4.92	4.76	4.60	4.68	4.79
4 A	5.62	5.43	5.36	5.05	5.24	5.34
5	4.18	4.34	4.12	4.10	4.07	4.16
5 A	5.69	4.64	4.47	4.58	4.53	4.78
6	4.24	4.12	4.05	4.10	4.08	4.12
6 A	4.41	4.42	4.31	4.47	4.42	4.41
7	3.29	3.34	3.29	3.54	3.29	3.35
7 A	3.38	3.49	3.48	3.68	3.48	3.50

	NDIR CO_2, VOLUME % (WET)					
	RUN NUMBER					AVERAGE OR TYPICAL VALUE
MODE	2	3	4	5	6	
1	6.84	7.14	7.12	7.84	7.40	7.27
1 A	3.71	4.77	4.36	5.18	5.92	4.79
2	8.22	7.82	7.61	8.52	8.40	8.11
2 A	6.55	6.32	3.96	4.83	4.23	5.18
3	8.35	7.92	7.66	8.56	8.39	8.18
3 A	7.19	5.04	4.03	6.07	6.71	5.81
4	6.32	6.44	6.06	6.77	6.73	6.46
4 A	4.77	4.90	3.96	5.04	5.04	4.74
5	5.90	5.86	5.52	6.37	6.00	5.93
5 A	4.36	4.70	3.71	3.64	4.77	4.24
6	4.28	3.96	4.02	4.78	4.72	4.35
6 A	3.09	2.29	2.62	4.16	3.52	3.14
7	3.26	3.22	3.18	3.20	3.26	3.22
7 A	2.51	1.91	2.56	2.62	2.29	2.38

TEST DATA ON MERCURY 650 OUTBOARD MOTOR

2/21/72 - 2/28/72 11-2869-01

	CHEMILUMINESCENT NO_x, ppm (WET)					
	RUN NUMBER					AVERAGE OR TYPICAL VALUE
MODE	2	3	4	5	6	
1	186	156	171	170	182	173
1 A	186	155	167	166	157	166
2	223	320	182	174	210	222
2 A	220	269	176	152	235	210
3	77	106	70	74	66	79
3 A	88	118	69	83	73	86
4	12	24	16	24	18	19
4 A	12	18	10	22	16	16
5	6	8	6	9	8	7.4
5 A	4	5	5	6	5	5.0
6	7	7	6	9	8	7.4
6 A	3	3	4	5	4	3.8
7	6	6	6	8	7	6.6
7 A	4	4	5	5	4	4.4

	CHEMILUMINESCENT NO, ppm (WET)					
	RUN NUMBER					AVERAGE OR TYPICAL VALUE
MODE	2	3	4	5	6	
1	170	138	142	148	176	155
1 A	181	138	153	142	142	151
2	201	231	170	110	198	182
2 A	215	255	176	88	225	192
3	66	98	58	64	62	70
3 A	78	107	61	76	69	78
4	8	16	10	16	12	12
4 A	8	12	10	17	11	12
5	2	3	2	4	4	3.0
5 A	2	2	1	2	3	2.0
6	4	4	4	4	5	4.2
6 A	2	2	2	3	3	2.4
7	3	4	5	5	4	4.2
7 A	2	2	4	3	3	2.8

TEST DATA ON MERCURY 650 OUTBOARD MOTOR

2/21/72 - 2/28/72 11-2869-01

	NDIR NO, ppm (WET)					
	RUN NUMBER					AVERAGE OR TYPICAL VALUE
MODE	2	3	4	5	6	
1	142	130	130	117	155	135
1 A	155	131	147	100	116	130
2	183	174	162	118	140	155
2 A	179	139	195	115	155	157
3	75	80	90	61	68	75
3 A	76	76	100	53	69	75
4	41	38	———	27	41	37
4 A	23	46	———	15	30	28
5	28	58	———	32	45	41
5 A	15	53	———	30	38	34
6	46	64	———	46	56	53
6 A	38	69	———	38	46	48
7	57	87	61	55	72	66
7 A	53	69	61	46	61	58

	POLAROGRAPHIC O_2, VOLUME % (WET)					
	RUN NUMBER					AVERAGE OR TYPICAL VALUE
MODE	2	3	4	5	6	
1	6.5	5.1	5.3	5.1	5.0	5.4
1 A	6.4	6.0	6.4	6.0	6.1	6.2
2	5.3	4.8	4.9	4.6	4.6	4.8
2 A	6.4	5.5	6.3	5.5	5.3	5.8
3	3.9	3.9	4.1	3.9	4.0	4.0
3 A	4.9	4.8	4.8	4.9	4.9	4.9
4	5.0	5.0	4.9	4.6	5.0	4.9
4 A	5.8	5.9	5.9	5.4	5.9	5.8
5	6.7	6.4	6.2	5.8	6.2	6.3
5 A	7.8	7.3	6.9	6.8	7.0	7.2
6	8.5	8.6	8.1	7.2	7.7	8.0
6 A	9.2	9.5	8.9	8.3	8.4	8.9
7	10.4	10.6	10.1	9.7	10.1	10.2
7 A	11.3	11.5	10.8	10.4	10.7	10.9

TEST DATA ON MERCURY 650 OUTBOARD MOTOR

2/21/72 - 2/28/72 11-2869-01

	FUEL CONSUMPTION, lb_m/hr					
	RUN NUMBER					AVERAGE OR TYPICAL VALUE
MODE	2	3	4	5	6	
1	46.9	46.9	45.7	46.4	44.8	46.1
1 A	47.4	47.1	46.1	46.5	46.7	46.8
2	36.9	37.5	37.7	37.0	37.3	37.3
2 A	36.5	37.2	38.2	37.2	37.0	37.2
3	24.7	24.4	24.4	25.0	24.9	24.7
3 A	24.9	24.4	24.4	24.9	24.9	24.7
4	16.4	17.3	16.8	17.8	16.9	17.0
4 A	16.4	17.5	16.8	17.9	17.3	17.2
5	12.0	12.2	11.8	12.1	11.8	12.0
5 A	12.0	12.5	12.1	11.8	11.7	12.0
6	10.4	10.3	10.4	10.7	11.0	10.6
6 A	10.6	10.4	10.4	10.7	11.1	10.6
7	7.14	6.89	7.03	8.89	8.08	7.61
7 A	7.09	7.06	6.81	8.56	8.02	7.51

	FUEL CONSUMPTION, g/hr					
	RUN NUMBER					AVERAGE OR TYPICAL VALUE
MODE	2	3	4	5	6	
1	21,300	21,300	20,700	21,000	20,300	20,900
1 A	21,500	21,400	20,900	21,100	21,200	21,200
2	16,700	17,000	17,100	16,800	16,900	16,900
2 A	16,600	16,900	17,300	16,900	16,800	16,900
3	11,200	11,100	11,100	11,300	11,300	11,200
3 A	11,300	11,100	11,100	11,300	11,300	11,200
4	7440	7850	7620	8070	7670	7710
4 A	7440	7940	7620	8120	7850	7800
5	5440	5540	5350	5490	5350	5440
5 A	5440	5670	5490	5350	5310	5440
6	4720	4670	4720	4850	4990	4810
6 A	4810	4720	4720	4850	5030	4810
7	3240	3130	3190	4030	3670	3450
7 A	3220	3200	3090	3880	3640	3410

SPECIAL TEST DATA ON MERCURY 650 OUTBOARD MOTOR

	FIA HYDROCARBONS, ppm C $\times 10^{-4}$ (WET)								
	TEST NUMBER								
MODE	1	2	3	4	5	6	7	8	9
1	5.19	5.27	5.29	5.08	5.04	5.33	6.09	5.21	5.16
1 A	4.20	3.92	3.14	3.30	3.80	4.46	5.28	4.00	3.64
1 B	4.00	3.70	3.12	3.20	3.50	4.08	4.92	3.82	3.56
3	3.83	3.75	3.91	3.66	3.85	3.64	3.99	3.87	3.73
3 A	2.65	2.45	2.46	2.52	2.87	2.77	3.18	2.86	2.52
3 B	2.48	2.41	2.37	2.28	2.64	2.48	2.90	2.67	2.43
5	6.20	6.93	6.83	6.73	6.65	6.81	6.63	6.75	6.59
5 A	5.04	5.20	5.06	4.96	5.56	5.68	5.80	5.28	4.90
5 B	4.82	4.80	4.68	4.86	5.30	5.44	5.48	5.02	4.76
7	9.53	10.00	9.17	9.20	9.00	8.60	9.07	9.10	8.90
7 A	8.20	8.40	7.30	7.65	7.80	7.95	7.75	8.10	6.95
7 B	8.00	8.40	7.25	7.55	7.55	7.75	7.65	8.05	6.90

	NDIR HYDROCARBONS, ppmC $\times 10^{-4}$ (WET)								
	TEST NUMBER								
MODE	1	2	3	4	5	6	7	8	9
1		2.63	2.51	3.14	3.23	3.21	4.90	3.43	2.96
1 A		3.75	3.14	3.45	3.86	3.69	5.32	3.81	3.39
1 B		3.56	3.18	3.41	3.73	3.49	5.23	3.77	3.25
3		2.09	2.15	2.16	2.25	2.28	3.52	2.45	2.12
3 A		2.79	2.48	2.55	2.76	2.68	3.94	2.96	2.50
3 B		2.48	2.34	2.48	2.65	2.65	3.99	2.84	2.45
5		4.13		4.48	4.63	4.72		3.98	3.46
5 A		4.84		5.02	5.52	4.97		4.42	3.80
5 B		4.83		4.90	5.67	5.09		4.54	4.38
7		7.32		7.18	8.44	7.71		7.91	5.45
7 A		7.95		7.56	8.85	8.09		8.41	5.92
7 B		7.81		7.55	9.19	8.23		8.69	6.07

SPECIAL TEST DATA ON MERCURY 650 OUTBOARD MOTOR

	NDIR CO, VOLUME % (WET)								
	TEST NUMBER								
MODE	1	2	3	4	5	6	7	8	9
1	2.99	3.07	3.15	2.99	3.18	3.23	3.15	3.19	3.25
1 A	3.34	3.34	3.54	3.25	3.50	3.41	3.51	3.29	3.60
1 B	3.32	3.53	3.58	3.34	3.51	3.48	3.56	3.56	3.58
3	3.43	3.17	3.42	3.28	3.57	3.09	3.29	3.24	3.16
3 A	3.70	3.50	3.98	3.56	3.93	3.25	3.68	3.60	3.53
3 B	3.96	3.40	3.76	3.68	3.68	3.58	3.85	3.60	3.51
5	4.33	4.22	4.36	4.27	4.33	4.15	4.34	4.38	4.23
5 A	4.88	4.70	4.73	4.64	4.78	4.53	4.76	4.81	4.58
5 B	4.82	4.70	4.70	4.64	4.84	4.58	4.81	4.81	4.58
7	3.76	3.74	3.78	3.64	3.91	3.77	3.17	3.59	3.96
7 A	3.92	3.83	3.92	3.81	4.04	3.98	3.50	3.78	4.12
7 B	3.89	3.82	3.89	3.73	4.12	3.96	3.07	3.82	4.14

	NDIR CO_2, VOLUME % (WET)								
	TEST NUMBER								
MODE	1	2	3	4	5	6	7	8	9
1	8.56	7.68	7.47	7.21	7.35	7.38	7.72	7.34	7.26
1 A	6.56	5.40	3.68	3.94	5.64	6.75	7.46	6.10	4.36
1 B	5.72	4.90	3.90	3.90	4.64	6.00	6.63	5.08	4.10
3	8.59	8.57	8.04	7.89	8.04	8.22	8.59	8.13	8.12
3 A	6.83	5.86	5.04	3.97	6.17	7.37	8.33	6.72	5.30
3 B	6.04	5.32	4.13	3.71	5.74	6.51	7.37	5.92	3.97
5	5.93	6.00	5.88	5.30	5.67	5.71	6.14	5.84	5.77
5 A	4.70	4.69	3.84	3.22	4.90	5.12	5.86	4.76	3.62
5 B	4.13	3.71	3.06	2.89	3.86	4.73	5.26	4.00	3.42
7	3.30	3.33	3.41	2.97	3.31	3.37	3.53	3.15	3.67
7 A	2.81	2.65	2.07	1.99	2.76	3.09	3.28	2.59	2.51
7 B	2.51	2.34	1.88	1.77	2.52	2.74	2.98	2.56	2.57

SPECIAL TEST DATA ON MERCURY 650 OUTBOARD MOTOR

CHEMILUMINESCENT NO_x, ppm (WET)

MODE	TEST NUMBER								
	1	2	3	4	5	6	7	8	9
1	254	216	204	221	191	176	146	140	137
1 A	248	223	194	235	208	200	157	147	142
1 B	240	220	194	218	218	181	156	142	142
3	91	90	70	86	72	100	72	79	90
3 A	99	93	68	86	82	96	80	86	90
3 B	92	96	70	79	80	98	73	86	91
5	7	6	5	6	7	7	6	7	7
5 A	3	2	4	2	3	4	2	4	3
5 B	4	2	2	2	4	4	3	4	3
7	6	6	6	6	6	6	6	6	6
7 A	2	1	2	2	2	3	2	2	2
7 B	2	1	2	2	2	2	2	2	2

CHEMILUMINESCENT NO, ppm (WET)

MODE	TEST NUMBER								
	1	2	3	4	5	6	7	8	9
1	223	190	168	204	169	157	131	119	126
1 A	228	213	169	215	191	176	150	130	142
1 B	240	210	181	186	196	171	147	130	130
3	79	75	61	72	64	82	65	67	73
3 A	92	78	57	80	74	86	72	76	78
3 B	89	84	66	72	74	82	69	80	83
5	3	1	3	2	2	2	1	3	2
5 A	2	0	2	1	2	2	1	2	1
5 B	2	0	2	1	1	1	1	2	1
7	3	2	3	2	3	4	3	3	3
7 A	2	1	2	1	2	2	2	2	2
7 B	2	0	2	1	2	2	2	2	2

SPECIAL TEST DATA ON MERCURY 650 OUTBOARD MOTOR

	NDIR NO, ppm (WET)								
	TEST NUMBER								
MODE	1	2	3	4	5	6	7	8	9
1	161	139	161	168	150	145	134	119	126
1 A	178	162	155	179	170	147	140	127	120
1 B	183	154	151	158	155	147	150	128	116
3	78	62	69	76	64	71	80	80	81
3 A	84	65	69	80	64	76	84	88	84
3 B	76	64	72	72	57	64	84	84	80
5	35	30	46	47	30	33	50	42	39
5 A	26	26	38	34	26	26	46	34	34
5 B	26	26	38	38	26	26	46	38	38
7	70	60	80	68	59	64	72	77	62
7 A	61	46	65	53	46	53	72	72	50
7 B	61	46	61	53	50	54	76	72	53

	POLAROGRAPHIC O_2, VOLUME % (WET)								
	TEST NUMBER								
MODE	1	2	3	4	5	6	7	8	9
1	5.0	5.3	5.4	5.2	5.4	5.3	5.3	5.2	5.3
1 A	5.8	6.2	6.4	6.2	6.3	5.8	5.4	6.1	6.4
1 B	5.8	6.1	6.4	6.0	6.2	6.2	5.4	6.0	6.2
3	3.8	3.8	4.1	4.0	4.0	4.2	3.6	4.2	4.2
3 A	4.4	4.8	4.9	4.9	4.8	4.9	4.0	4.9	5.2
3 B	4.5	4.7	5.0	4.9	4.8	4.9	4.0	4.8	5.2
5	6.2	6.2	6.7	6.3	6.5	6.7	5.4	6.3	6.5
5 A	7.0	7.1	7.7	7.2	7.4	7.4	6.2	7.3	7.4
5 B	7.0	7.1	7.8	7.2	7.4	7.4	6.2	7.2	7.6
7	9.7	9.9	10.5	9.7	10.0	10.1	8.5	10.6	9.8
7 A	10.4	10.4	11.3	10.3	11.0	10.8	9.2	11.3	10.8
7 B	10.4	10.4	11.4	10.3	11.4	10.8	9.2	11.4	10.7

APPENDIX E

ESTIMATED STATE AND REGIONAL DISTRIBUTION OF OUTBOARD MOTORS, 1971

ESTIMATED STATE AND REGIONAL DISTRIBUTION OF OUTBOARD MOTORS, 1971(4)

Estimated Motors in Use as of December 31, 1971, by Region and State

Northern Region		Central Region		Southern Region	
State	Motors	State	Motors	State	Motors
Idaho	38,000	Colorado	35,000	Alabama	132,000
Maine	86,000	Connecticut	102,000	Arizona	40,000
Minnesota	333,000	Delaware	20,000	Arkansas	101,000
Montana	25,000	Dist. of Columbia	31,000	California	430,000
New Hampshire	44,000	Illinois	322,000	Florida	440,000
North Dakota	25,000	Indiana	186,000	Georgia	133,000
Oregon	122,000	Iowa	102,000	Louisiana	226,000
South Dakota	26,000	Kansas	72,000	Mississippi	61,000
Vermont	23,000	Kentucky	85,000	New Mexico	18,000
Washington	209,000	Maryland	130,000	North Carolina	118,000
Wisconsin	322,000	Massachusetts	192,000	Oklahoma	108,000
Wyoming	8,000	Michigan	478,000	South Carolina	108,000
		Missouri	201,000	Tennessee	144,000
		Nebraska	42,000	Texas	448,000
		Nevada	15,000		
		New Jersey	200,000		
		New York	593,000		
		Ohio	310,000		
		Pennsylvania	200,000		
		Rhode Island	34,000		
		Utah	32,000		
		Virginia	124,000		
		West Virginia	26,000		
Sub-total	1,261,000	Sub-total	3,532,000	Sub-total	2,507,000

All-Region Total - 7,300,000